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SPACE NUCLEAR THERMAL PROPULSION PROGRAM FINAL REPORT

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Final Report

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14. Abstract The SNTP Program was an advanced technology development effort aimed at providing the Nation a new, dramatically higher performing rocket engine that would more than double the performance of the best conventional chemical rocket engines. The program consisted of three phases. Phase I ran from November 1987 through September 1989. The objective of this phase was to verify the feasibility of the Particle Bed Reactor (PBR) as the propulsion energy source for the upper stage of a ground-based Boost Phase Intercept (BPI) vehicle. The BPI mission was of interest to the Strategic Defense Initiative Organization (SDIO) who sponsored the program. Phase II started under SDIO control and was transferred to the Air Force (AF) in October 1991. The BPI mission was de-emphasized, and engine requirements were revised to satisfy more general AF space missions. The goal of Phase II was to perform a ground demonstration of a prototypical PBR engine.

15. Subject Terms Space Nuclear Thermal Propulsion, Particle Bed Reactor, SNTP, Timberwind, Hydrogen

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Additional Reference Material

This Final Report provides an overview of the SNTP Program and summarizes the technical accomplishments of the program. Anticipating that nuclear propulsion and/or power systems will eventually be desired to expand our capabilities in space, the Air Force has archived all significant SNTP information to assist future development programs. The SNTP reference library was drawn from thousands of program documents and is now available as an electronic data base resident at the Air Force Phillips Laboratory. In the near future, the data base will also be available at two (2) DOE facilities - Sandia National Laboratories (SNL) and Knolles Atomic Power Laboratory (KAPL) - and ultimately, in approximately two (2) years, at the National Archives.

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List of Acronyms

ACRR	Annular Core Research Reactor
ALARA	As Low As Is Reasonably Achievable
ASTM	American Society for Testing and Materials
ATS	Advanced Top Stage
B&W	Babcock & Wilcox
BNL	Brookhaven National Laboratory
BOP	Balance of Plant
CDR	Critical Design Review
CFD	Computerized Fluid Dynamics
CIS	Commonwealth of Independent States
CM	Compression Moldings
CPO	Central Project Office
CSS	Coolant Supply System
CTE	Coefficient of Thermal Expansion
CTF	Contained Test Facility
CVD	Chemical Vapor Deposition
CX	Critical Experiment
DE	Demonstration Engine
DOE	Department of Energy
DRM	Design Reference Mission
DSB	Defense Science Board
EA	Environmental Assessment
EIS	Environmental Impact Statement
EIT	Engine Integration Test
ES&H	Environment, Safety, and Health
ESD&D	Engine System Design & Development
ETO	Earth to Orbit
ETS	Effluent Treatment System
FIT	Flow Instability Test
FSD	Fluid Systems Division - (Allied Signal)
FW	Filament Wound
GFY	Government Fiscal Year
GNFC	Grumman Net Flow Controller
GSO	Geostationary Orbit
GTA	Ground Test Articles or Ground Test Assembly
GTE	Ground Test Engine
GTO	GEO Transfer Orbit
HCF	Hot Cell Facility
HFIR	High Flux Integrated Reactor
HHGG	Hot Hydrogen Gas Generator
HTGR	High-Temperature Gas-cooled Reactors
HTSR	High-Temperature Spin Ring
ICBM	Intercontinental Ballistic Missile
ICS	Integrated Control System
IK	Infiltrated Kernel

IOC	Initial Operational Capability
INEL	Idaho National Engineering Laboratory
IPDR	Internal Preliminary Design Review
KKV	Kinetic Kill Vehicle
LANL	Los Alamos National Laboratory
LEO	Low Earth Orbit
LeRC	Lewis Research Center
MCF	Mixed Carbide Fuel
MCNP	Monte Carlo Nuclear Program
MEI	Maximally Exposed Individual
MPS	Master Program Schedule
NEPA	National Environmental Policy Act
NERVA	Nuclear Engine Rocket Vehicle Application
NET	Nuclear Element Test
NFPA	National Fire Protection Association
NGTF	Nuclear Ground Test Facility
NLS	National Launch Systems
NRC	Nuclear Regulatory Commission
NRE	Nuclear Rocket Engine
NSO	Nuclear Safe Orbit
NTP	Nuclear Thermal Propulsion
NTR	Nuclear Test Reactor or Rocket
NTS	Nevada Test Site
OMV	Orbit Maneuvering Vehicle
ORNL	Oak Ridge National Laboratory
OTV	Orbit Transfer Vehicle
PBR	Particle Bed Reactor
PDR	Preliminary Design Review
PHT	Particle Heating Test
PIE	Post Irradiation Examination
PIPET	Particle Bed Reactor Integral Performance Tester
PLC	Programmable Logic Controller
PMP	Project Management Plan
PMS	Propellant Management System
PNT	Particle Nuclear Test
PV	Pressure Vessel
QTA	Qualification Test Article
RFS	Reactor Flow Simulator
ROD	Record of Decision
ROTV	Return Orbit Transfer Vehicle
RT	Room Temperature
RTG	Radioisotope Thermoelectric Generators
RTM	Resin Transfer Moldings
SA	Safety Assessment
SAR	Safety Analysis Report or Special Access Required
SCV	Speed Control Valve
SDIO	Strategic Defense Initiative Organization

SEFIT	Subsequent FIT
SEI	Space Exploration Initiative
SIP	Safety Implementation Plan
SITL	System Integration & Test Laboratory
SLBM	Submarine Launched Ballistic Missile
SMTS	Saddle Mountain Test Station
SNAP	Space Nuclear Auxiliary Power
SNL	Sandia National Laboratories
SNM	Special Nuclear Material
SNTP	Space Nuclear Thermal Propulsion
SoRI	Southern Research Institute
SPM	Solid Propellant Motor
SRM	Solid Rocket Motor
STME	Space Transportation Main Engine
TNT	Transient Nuclear Test
TPA	Turbopump Assembly
TVC	Thrust Vector Control
UHM	Ultra High Modulus Fiber
UNC	United Nuclear Corporation
UPS	Uninterruptible Power Supply
USAF	United States Air Force
WBS	Work Breakdown Structure

1.0 EXECUTIVE SUMMARY

1.1 Overview

The SNTP Program was an advanced technology development effort aimed at providing the Nation a new, dramatically higher performing rocket engine that would more than double the performance of the best conventional chemical rocket engines. The SNTP program had been aggressively developing a nuclear engine for over five years, expended close to $200M, and was well along the path of success, when in 1992 changing national priorities and security requirements, prompted by the end of the cold war and domestic economic pressures, resulted in a slow-up of the program and eventually, termination.

The program consisted of three phases, as shown in Figure 1-1. Phase I ran from November 1987 through September 1989. The objective of this phase was to verify the feasibility of the Particle Bed Reactor (PBR) as the propulsion energy source for the upper stage of a ground-based Boost Phase Intercept (BPI) vehicle. The BPI mission was of interest to the Strategic Defense Initiative Organization (SDIO) who sponsored the program. Due to the nature of the mission and the technology being developed, the program was classified Secret, Special Access Required (S/SAR). Phase I was completed with preliminary design reviews (PDR) for the engine and an experimental flight test vehicle to demonstrate the technologies needed for the interceptor. The flight test was configured to safely test the nuclear upper stage using an MX first stage. The nuclear stage was to be ignited above the atmosphere and would reach a velocity well in excess of that required for earth escape.

Phase II started under SDIO control and was transferred to the Air Force (AF) in October 1991. The BPI mission was de-emphasized, and engine requirements were revised to satisfy more general AF space missions. The goal of Phase II was to perform a ground demonstration of a prototypical PBR engine. It was envisioned that a flight demonstration would be conducted in Phase III of the Program using a Atlas IIas launch vehicle to place the SNTP system in a nuclear safe orbit. The SNTP system would then be used to send a scientific payload on a earth escape trajectory. There was no longer a need for the SAR security classification, and the program classification was reduced to Secret, LIMDIS (Limited Distribution) in late 1991 when the program became known as the Space Nuclear Thermal Propulsion Program. The LIMDIS controls were lifted in early 1993, and only those nuclear technology portions of the program under the cognizance of the Department of Energy (DOE), remain classified as Secret or Confidential/Restricted Data (RD).

The program was terminated in January 1994, prior to the completion of Phase II. The flight demonstration of the SNTP system in Phase III was, therefore, never initiated. This report summarizes Phase II of the program.

The Particle Bed Reactor (PBR) concept that was the basis of the SNTP engine system was conceived by Dr. James Powell of Brookhaven National Laboratory in the late 70's. Dr. Powell presented his concept to Grumman in 1982, and it was quickly recognized that the PBR's features of small size and light weight made it ideal for space applications. Over the next several years, a team was assembled to study and evaluate the engineering feasibility of the PBR. Numerous presentations were made promoting the impressive capabilities of PBR-

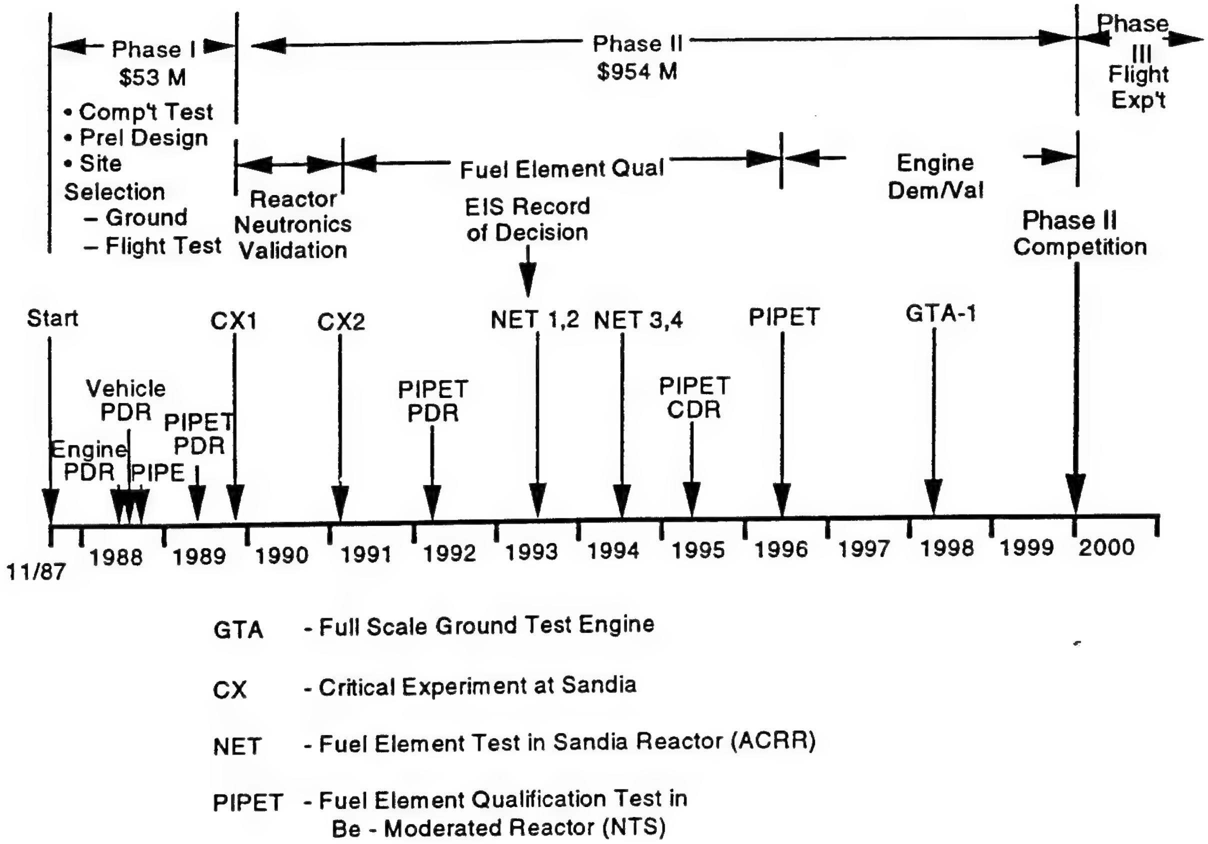


Figure 1-1 Program Master Schedule

based systems for space applications that culminated in the start of a development program (Phase I) in 1987. The several diverse organizations that were assembled to conduct the program included two (2) national laboratories; Sandia National Laboratories (SNL) and Brookhaven National Laboratory (BNL); and an industrial team that included Grumman, Babcock & Wilcox, Allied Signal, Aerojet, Hercules, General Dynamics and several smaller specialized companies as shown in Figure 1-2. Near the end of the program, new advanced nuclear fuel technology was uncovered in the former Soviet Union at the Russian Scientific Industrial Association "Lutch." Negotiations had been completed with "Lutch" and a contract was about to be placed with them to import the technology, thus making the program international in scope.

The SNTP Program was from its inception, a dynamic and sometimes controversial program that struggled to maintain the consistent, high priority mission "pull" required to sustain program focus and funding. Started as a streamlined, fast-track program to satisfy an urgent defense mission, the original mission need subsided, overall cost became more important, and the program underwent several redirections in programmatic and technical approaches and goals, including a change in government sponsors. Over its relatively short existence, the program succeeded in establishing the scientific data base and engineering design, analysis and technical evidence to convince two (2) Defense Science Boards, the Gen. Stafford Synthesis Group, and others, that a space nuclear thermal propulsion system based on a Particle Bed Reactor could be developed. Those prominent panels and independent review teams concurred that the PBR could provide a safe, reliable, more cost effective and higher performance rocket engine that could provide a giant leap in U.S. space rocket capabilities.

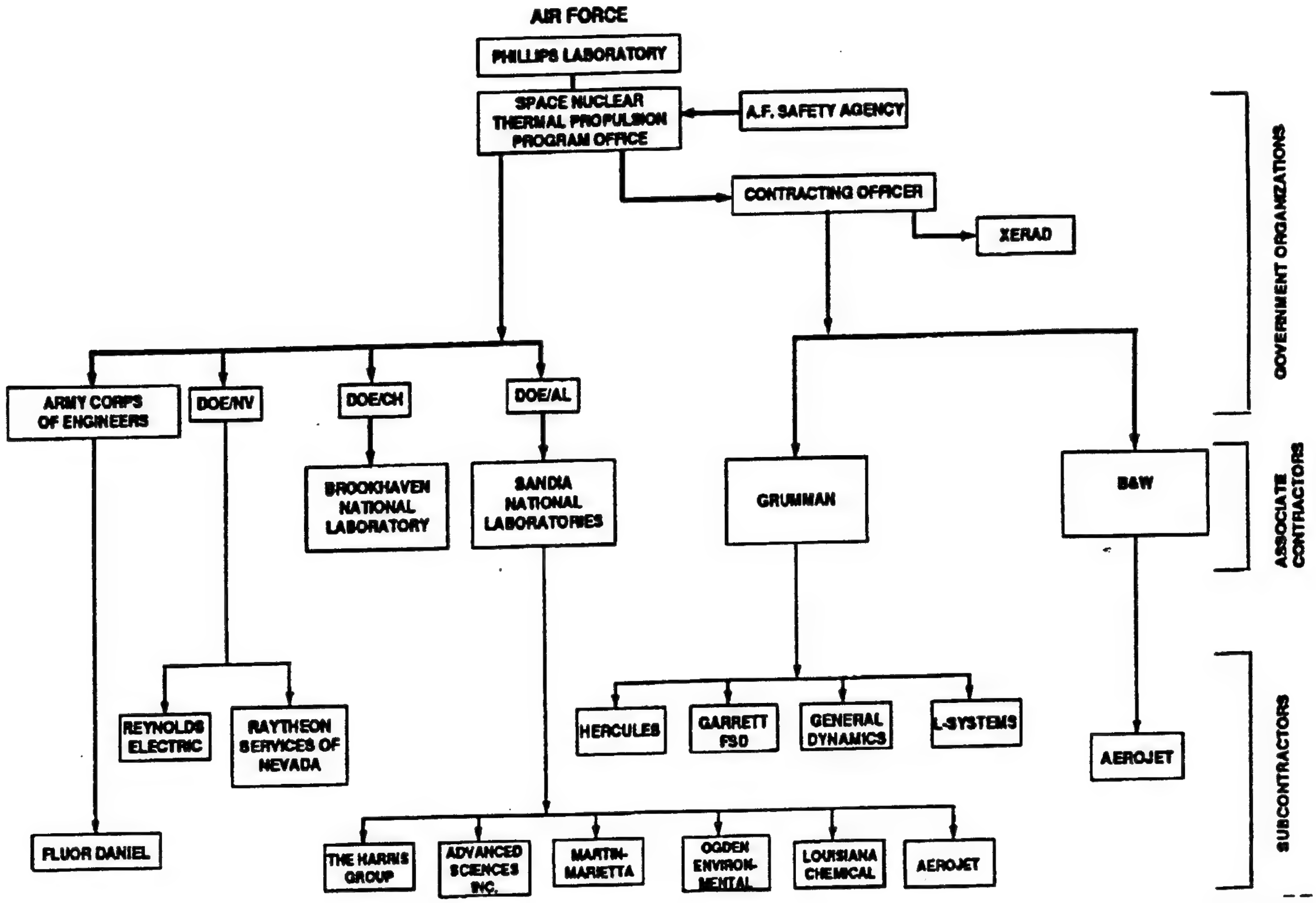


Figure 1-2 SNTP Organization

The reality of modern day program cost constraints had a driving influence on the approach to the program, especially the testing approach. The earlier NERVA Program had spent \$1.4B (then-year dollars, over \$5B in today's dollars) to test several total engine systems which was clearly not realistic for the SNTP Program. Nuclear testing in the SNTP Program required a new facility to accommodate the high-power densities in the PBR. The new facility would be subjected to much more stringent environmental protection requirements than were the test facilities for NERVA. The approach to the SNTP Program, shown in Figure 1-3, therefore was based on a more economical step-wise approach to system development testing, where system components would be proven at the lowest level of assembly before progressing to higher level tests. Only after the key system elements had been validated would engine level tests be conducted. Total engine system nuclear tests would be limited to scaled-down systems that would have technology traceable to flight type engines. This approach to the SNTP test program would have resulted in a ground demonstration test in the year 2000, with a total cost of approximately \$1B. New fresh ideas that were emerging near the end of the program, e.g. the use of the underground nuclear test facilities in Nevada, were being pursued in an effort to further reduce the total program cost.

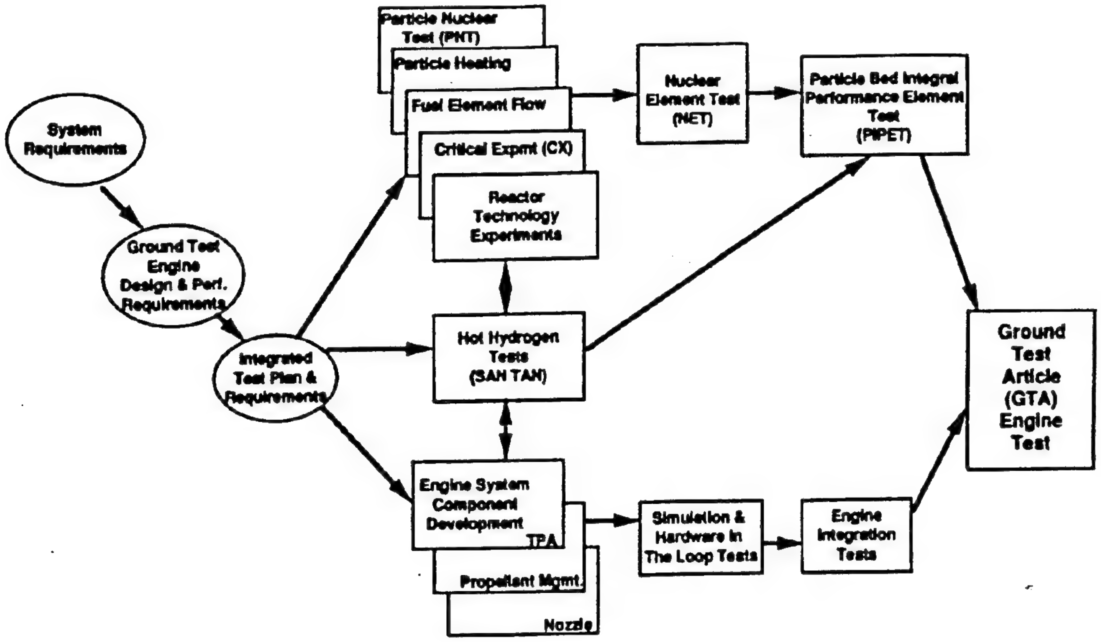


Figure 1-3 Program General Approach

1.2 Mission Driven Requirements

Throughout Phase II of the program, focus was maintained on the ultimate applications for such a revolutionary technology. Military and civil space missions that included high-speed interceptors, launch vehicle upper stages, and orbit transfer/maneuvering vehicles (OTV/OMV) were analyzed and conceptual/ preliminary designs formulated. In most cases the performance improvements relative to existing capabilities were found to be dramatic, and in some cases, even enabling. Typical mission benefits, derived from these analyses, are shown in Figure 1-4 for upper stage applications, and Figure 1-5 for OMV applications. Payload improvements from 2-to-4 times could be obtained, and high energy missions, e.g., OMV Payload Replacement/Retrieval (LEO-GEO-LEO), could be enabled by SNTP.

The specific mission design requirements were fused into a general engine performance specification that served to frame the target goals of a point design engine system. The performance goals for the generic flight-type engine were challenging. The goals were to achieve a specific impulse of 1000 seconds, with a thrust-to-weight ratio of 25:1 to 35:1 for engine systems from 20,000-to-80,000 pounds of thrust. A strawman engine design was developed. This design was for a 40,000 pound thrust class (1000 MW_t) engine that would meet the primary AF mission as an upper stage propulsion system, and several other missions as well. This engine, which utilized a hot-gas bleed cycle is shown in Figure 1-6. Also shown in the figure are the primary organizations responsible for the development of the major components. The performance that could be attained with this design was an I_{sp} of 930 seconds and a thrust to weight of 20:1. The reduction in the performance relative to the goals, was the result of incorporating additional safety criteria and robustness for multiple restarts that had not existed prior to the transition from SDIO to AF applications. Although lower than

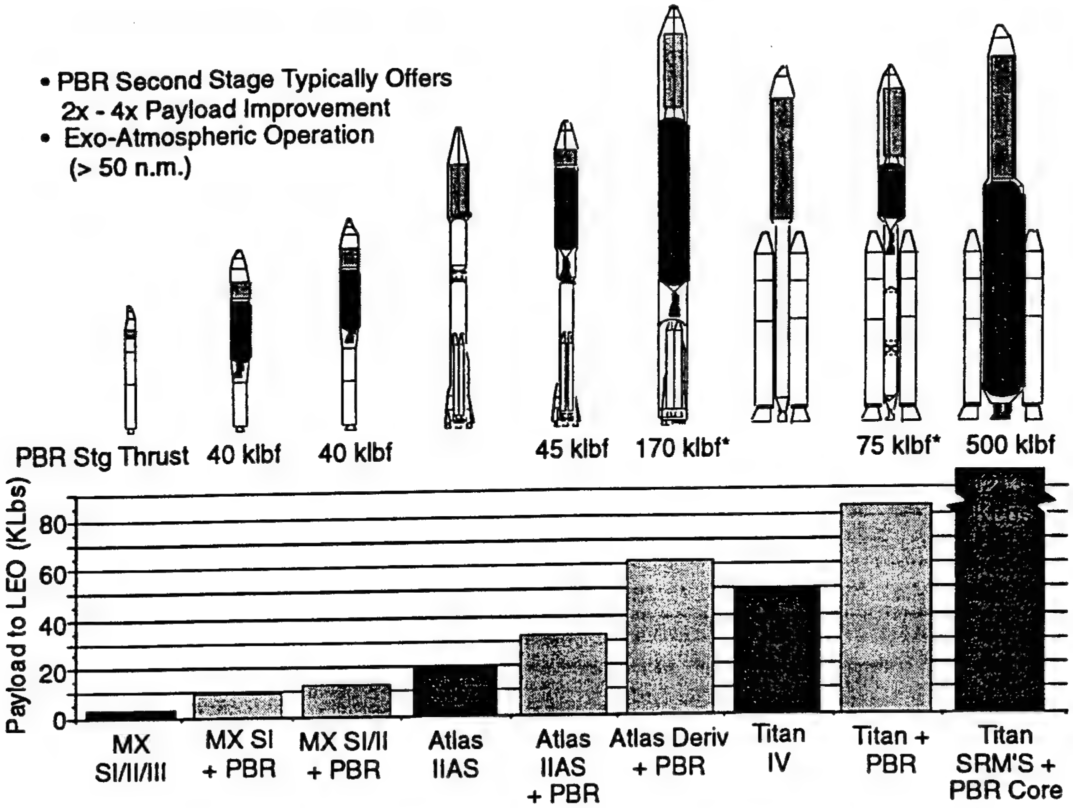


Figure 1-4 Typical Upper Stage Applications

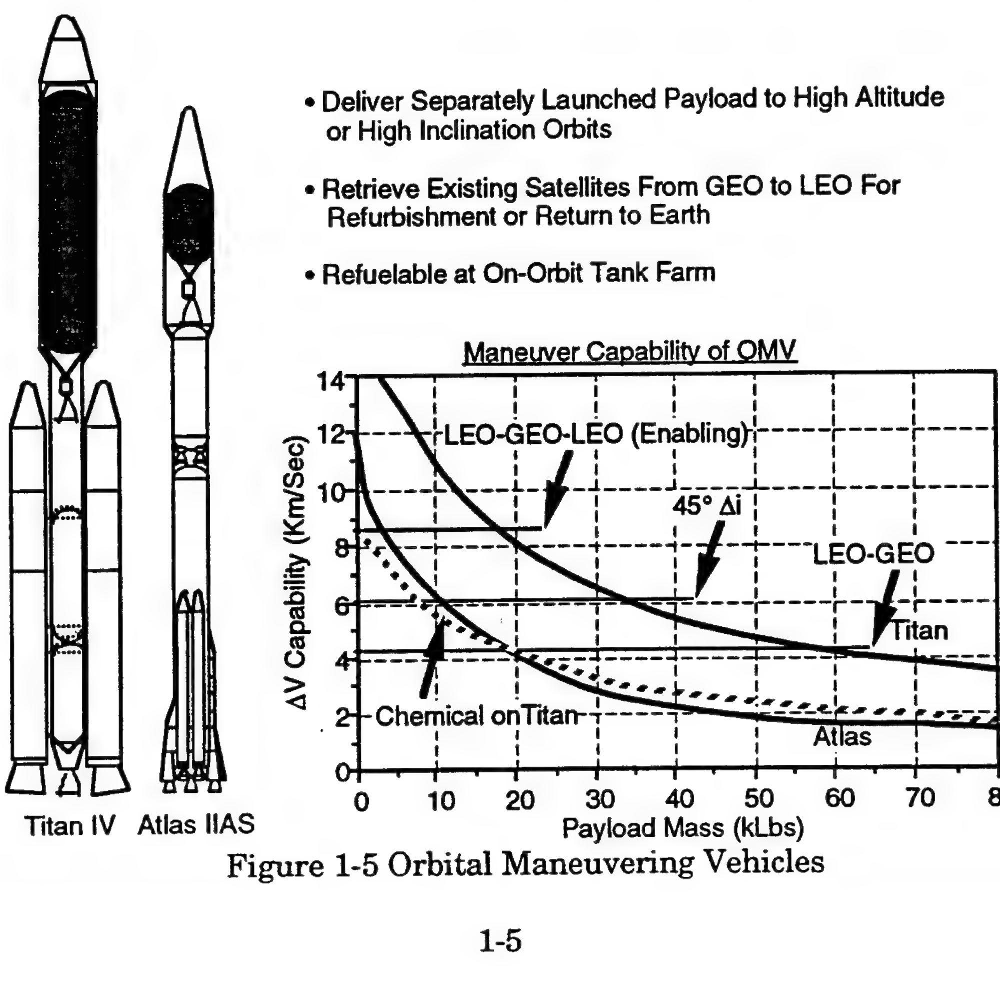


Figure 1-5 Orbital Maneuvering Vehicles

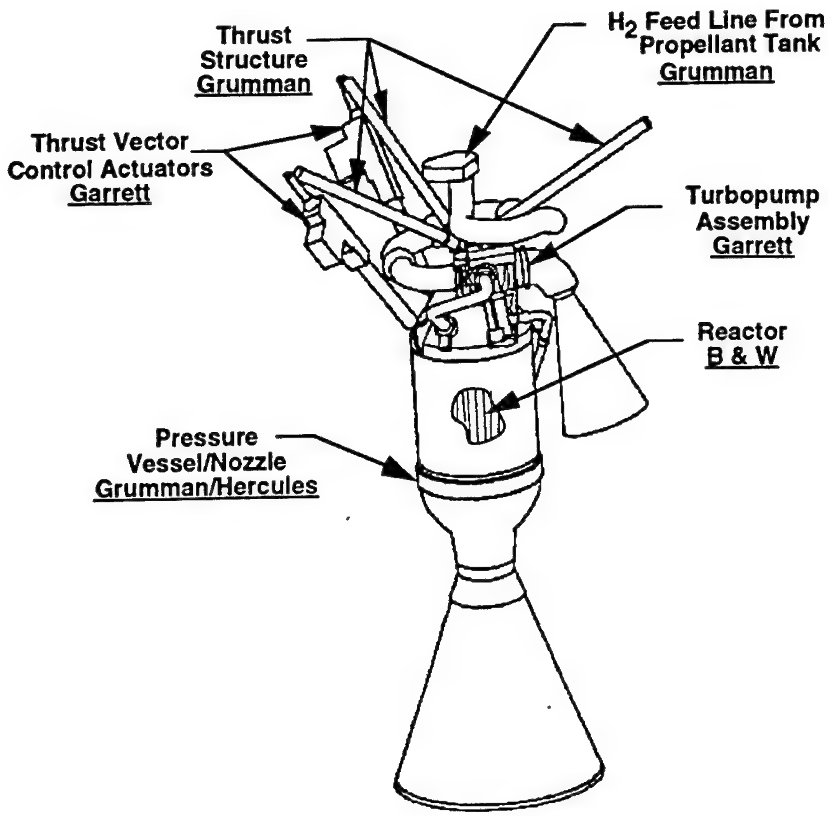


Figure 1-6 SNTP Engine

the program goals, this level of performance was still mission enhancing/enabling. To put the SNTP performance into perspective, NERVA derivative engines which were being studied for the NASA/Space Exploration Initiative had predicted thrust-to-weight ratios of 4:1 to 8:1, and I_{sp}'s in the 850 second range. The major performance improvements offered by the SNTP engine can be attributed to the direct cooling of the fuel particles, which enables a higher core power density (compactness), and lower temperature difference between the fuel and the coolant (higher outlet gas temperature and I_{sp}).

As in all endeavors dealing with nuclear energy, concern with safety and the protection of the environment must be in the forefront. The SNTP Program had declared safety as its number one priority. A comprehensive SNTP Safety Policy Document was completed that established the stringent safety policy and requirements under which the program would be conducted. A major program accomplishment in this arena was the completion of the Final Environmental Impact Statement. The environmental impact analysis process included both scoping meetings and public hearings within the regions of interest associated with the two candidate test sites; the Nevada Test Site and the Idaho National Engineering Laboratory. A Notice of Availability was published in the Federal Register and a Record of Decision was pending at the time of SNTP Program termination.

1.3 Test Facilities

With the basic performance parameters established, attention was directed to defining a cost-effective approach to the ground test demonstration of the technologies that would be required by such an engine. The development of a nuclear ground test facility was a high priority from the inception of the program. It was recognized early on that there were no facilities in the western world that could test the high power density SNTP fuel elements. In addition, existing facilities in Nevada used to test NERVA/Rover engines were unsuitable, particularly from an ES&H standpoint. As shown in Figure 1-7, the facility that was being planned underwent continuous evolution and change. It started out as a focused single use facility for testing SNTP fuel elements and engines, expanded to a "National Propulsion Test Facility" where it would also be used to test other nuclear propulsion concepts, and finally, with the realization that a "do everything" facility was not affordable with the available funding sources, it was refocused and simplified to reduce its' cost. The test facility was the major program cost driver.

The ground test facility, shown in Figure 1-8 was initially divided into an element tester called the Particle Bed Reactor Integral Performance Element Tester (PIPET) and a full scale area with five engine test stands. The design of PIPET was developed to significant detail and

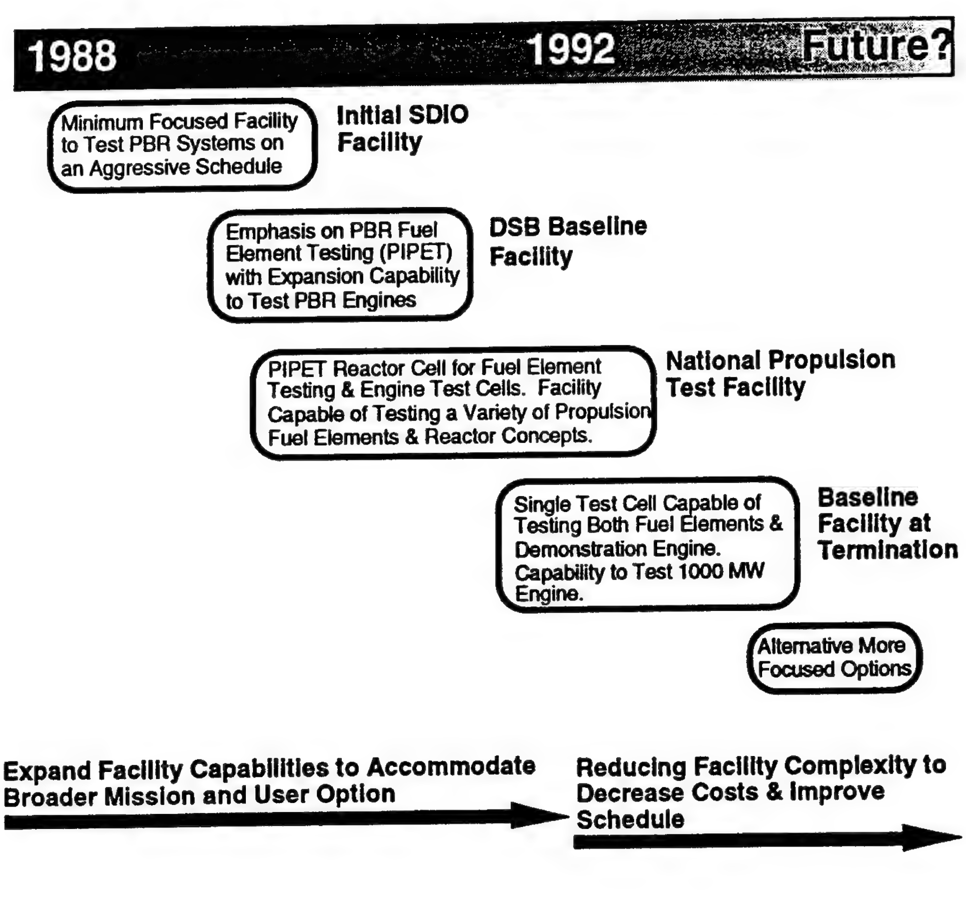


Figure 1-7 Timeline for Ground Test Facility

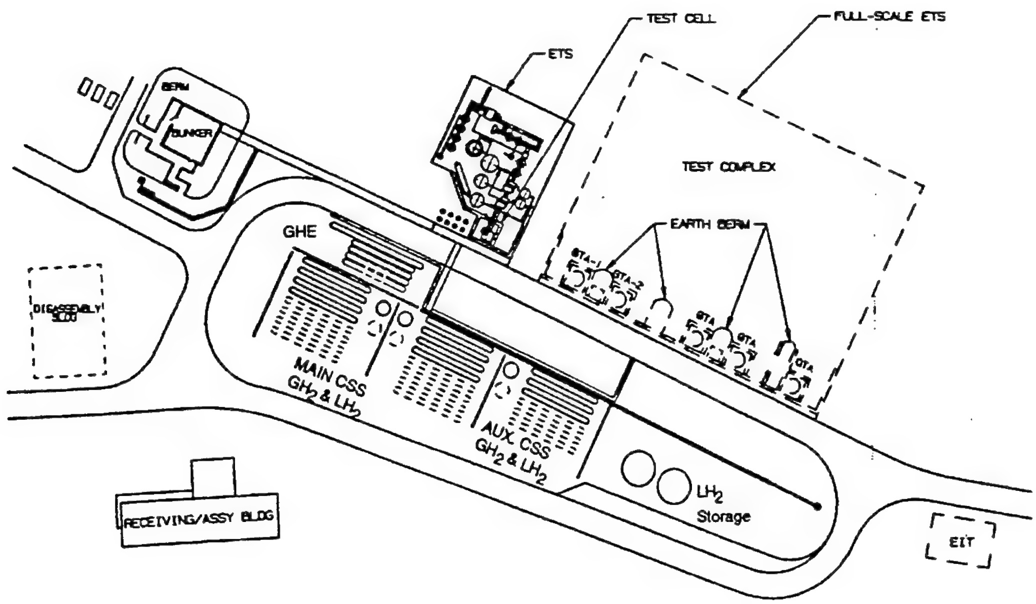


Figure 1-8 Saddle Mountain Test Site Located at Nevada Test Site

a formal Preliminary Design Review (PDR) was held at SNL. This review was chaired by the AF with other government agencies and consultants taking part in the review and submitting formal action items, which were successfully dispositioned. With this very detailed design as a baseline, efforts were concentrated on reducing the projected costs.

Development of the SNTP engine also required non-nuclear test facilities capable of testing with cryogenic and high temperature (3000 K) hydrogen. This facility was required to develop many of the engine components, e.g., the turbopump, feed valves, nozzles (subscale), and internal reactor components (hot frit). It was located in the remote San Tan Test Site operated by Allied Signal on land leased from the Gila River Indian Community. San Tan was well along in construction, as shown in the aerial photograph, Figure 1-9, when the program was terminated.

1.4 Major Technical Issues and Accomplishments

The development of the major components was in varying degrees of maturity due, to a large extent, to the program priorities which were dictated by funding restraints. Multi-year plans were generated based on program goals and funding expectations, which were often not realized. This required that program priorities and funding allocations be revised, which caused significant loss of efficiency and reduced progress. Even with these continuing programmatic problems, very significant technical progress was made.

The two major technical issues facing the development of the SNTP engine were reactor related: (1) the ability of the fuel particles to operate at very high temperature (~3500 K), and (2) the thermal-hydraulic and structural performance of the fuel element. Partial success was achieved in both these areas, and sufficient understanding of the problems was gained to reasonably expect that their development would be successful. Based upon the progress in

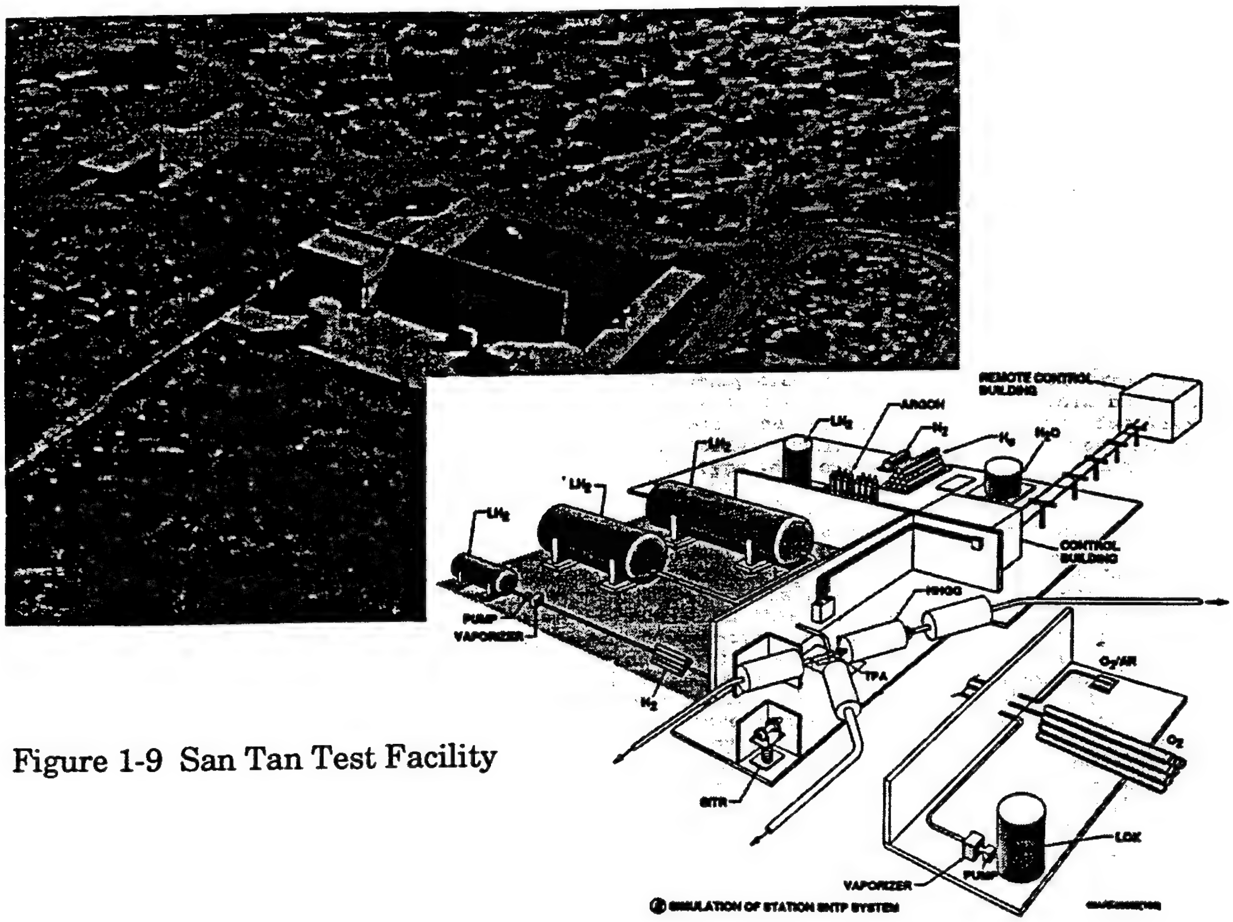


Figure 1-9 San Tan Test Facility

these areas there was a substantial effort to define reactor and balance of plant designs and components that could accommodate the stringent operating specifications of the SNTP Program.

1.4.1 Nuclear Fuel

A "Baseline Fuel" particle, shown in Figure 1-10, was developed with a maximum temperature capability of ~2800 K. This particle was based on internal gelation technology transferred from Oak Ridge National Laboratory to Babcock & Wilcox (B&W), and provided the program with a fuel that could be used in nuclear fuel element development tests (NET) and in the Critical Experiment (CX). Initially, parallel paths for the development of a high temperature fuel were pursued. These development paths were the infiltrated kernel (IK) and the mixed carbide (MC) particles. The IK fuel was a lighter fuel that held the promise of higher temperature capability, since it could operate with the uranium in a liquid state. Early problems of fabricating the particles and fissile fuel loading were resolved and demonstrated on the laboratory scale. The remaining issue was to demonstrate that the particle, with its protective coating of zirconium carbide, would survive the corrosive high temperature hydrogen environment.

In 1992 the Program Management Team determined that development of both advanced fuel types would no longer be affordable. Initially a decision was made to pursue

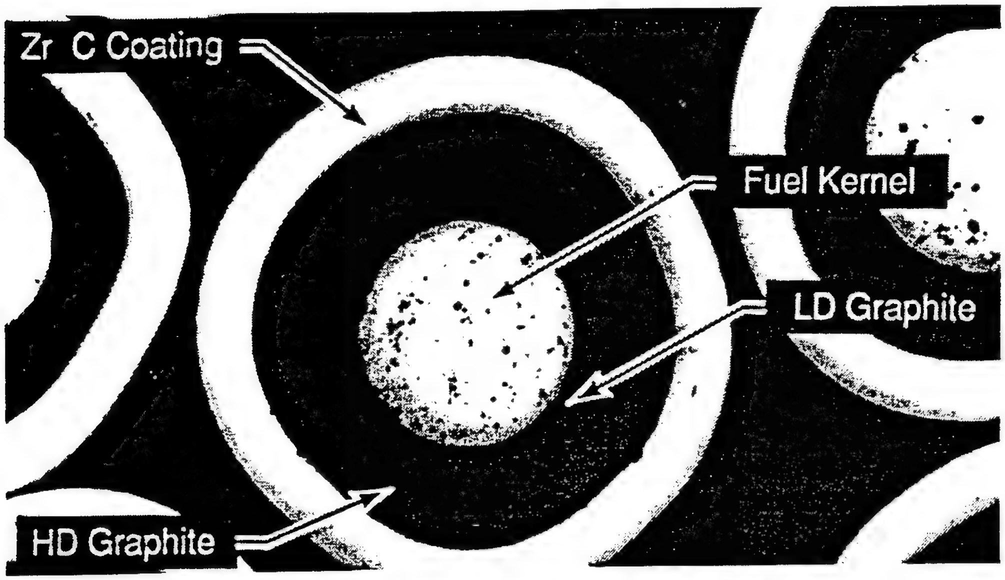


Figure 1-10 A Baseline Fuel Particle: UC_{2-x} Kernel, Pyrocarbon Layers with an Outer Coating of ZrC or NbC. The particle is ~0.5 mm in Diameter.

the IK particle because of its higher performance potential, and discontinue development of the MC particle. However, B&W did demonstrate MC fuel particle temperature in excess of 3100 K late in the program. It also became known that nuclear thermal rocket engine development in the former Soviet Union (FSU) had produced an MC fuel capable of temperatures of ~3500 K. The Program then performed an evaluation of the SNTP fuel development approach, using the expertise of noted nuclear fuel scientists. Upon their recommendation, development of the MC fuel would be pursued including the importation of FSU technology, and development of the IK particle would proceed at a low-level research effort. A contract with NPO Lutch to provide MC particles for testing was subsequently negotiated and was approved by the Russian government.

1.4.2 Fuel Element

The basic building block of the SNTP Particle Bed Reactor is the fuel element. Fuel element development included many component tests and culminated in a test of a complete fuel element in partial prototypic conditions. This nuclear element test (NET) was conducted in SNL's Annular Core Research Reactor (ACRR), utilizing the experiment capsule shown in Figure 1-11.

Component tests prior to the NET experiment developed the cold and hot frits with a mechanical design that could accurately meter flow to the fuel bed, survive the hot hydrogen environment, and allow for thermal expansions of the components and the fuel bed. The cold frit consisted of a stainless steel platelet stack with a compliant layer to accommodate bed expansion. The hot frit was made of niobium carbide-coated graphite with drilled holes.

Considerable effort was also expended and significant progress made in the development of analytic models for the NET experimental apparatus, the hydrogen flow control

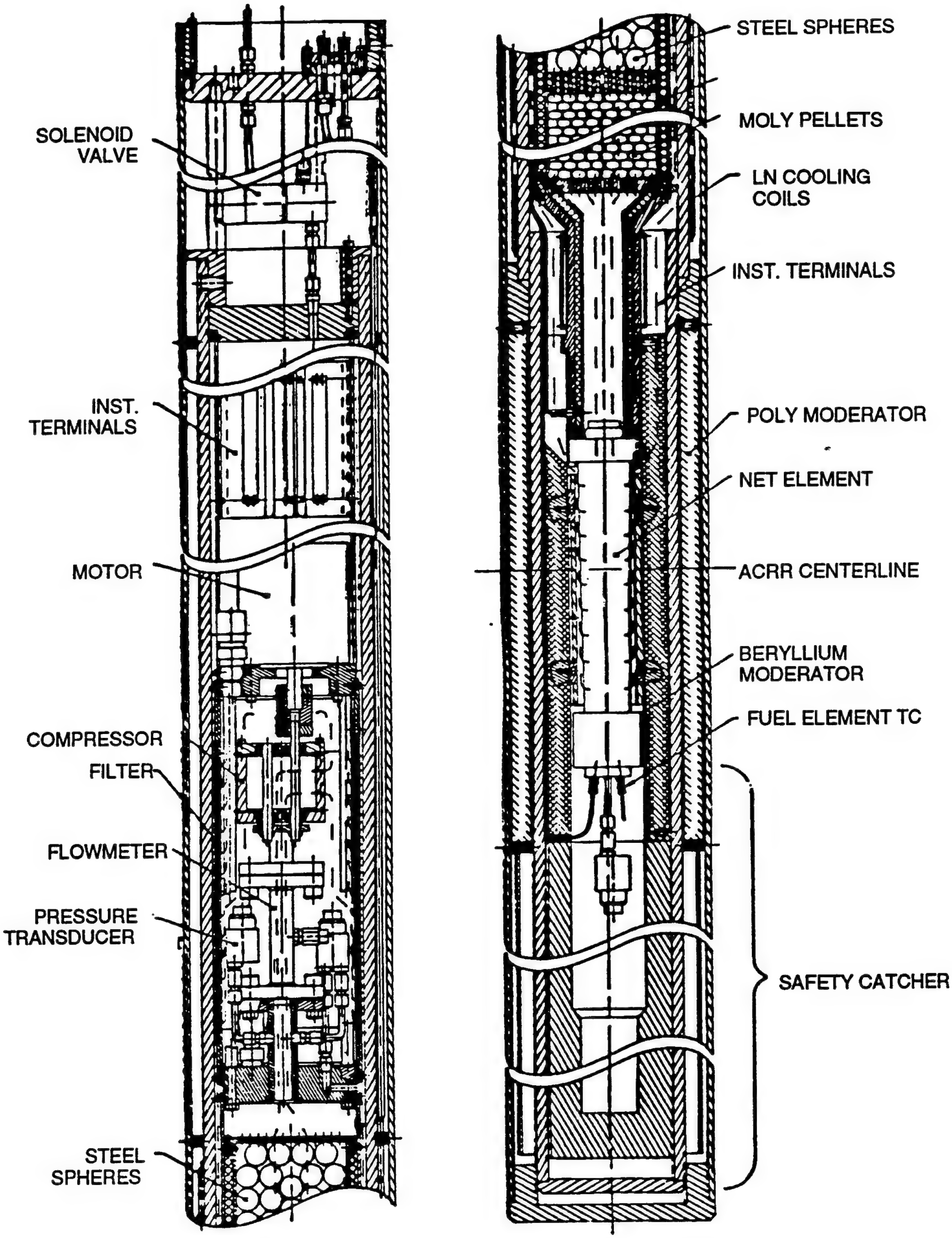


Figure 1-11 NET Experiment Capsule

system, and the thermal-hydraulic properties of the fuel element. Every team member participated in this work, and an open forum for the exchange of ideas, results, questions and agreements or disagreements was successfully carried out on a continuing basis.

The initial NET test runs were completed satisfactorily with the fuel element exhibiting stable flow characteristics. On the second run to a moderate temperature (≈1700 K) ACRR power irregularities halted testing. It was concluded and (later verified by an x-radiograph) that the ACRR power anomalies were indicative of potential fuel movement within the fuel element. The Program Office then authorized SNL and B&W to perform a minimal post irradiation examination (PIE), which confirmed the existence of circumferential breaks in the hot frit.

The postulated failure from analysis of the PIE results was excessive thermal stress on the hot frit. This conclusion was based on the appearance and location of the breaks. Post test analysis revealed that the breaks were located in the regions of maximum stresses, and that the fuel bed thermal expansion had been incorrectly calculated, probably contributing to the overstress condition. We believe that with designs already in development to improve the performance of the compliant layer, and with improved pretest analysis, future NET experiments with the same basic fuel element concept would have been successful.

In addition, world events occurring in parallel with the hot frit development and testing indicated that the FSU has done extensive research and development in the manufacture of carbide metals. If the capabilities were proven true, it would be possible to make a monolithic niobium carbide or zirconium carbide hot frit. At the end of the program, a draft contract between Grumman and NPO Lutch for supplying the carbide material for test was negotiated. The contract was approved by the Russian government, and the SOW was reviewed and concurred with by the Program Office.

1.4.3 Reactor Design

Reactor designs were developed that were able to meet stringent requirements of high temperature (3000 K) hydrogen; multiple starts and operation in the coast mode between burns at moderate temperature (~1200 K) to conserve cool-down propellant; rapid and stable startup (10 sec. to full thrust) with internal controls; deep throttling with a turndown ratio of 5:1; and internal redundant shutdown systems. The final design featured 37 fuel elements with beryllium cold frits, a beryllium and lithium-hydride moderator and a small (one inch thick) beryllium reflector: Figure 1-12.

The materials selected could accommodate the operating requirements, would be neutronically efficient, and optimized the reactor mass at ~500 kg. Thermal-hydraulics and neutronics codes were used to provide a reactor design that was fine tuned with coolant flow matching the internal power distribution in order to minimize overall coolant flow. The ability to accurately predict the internal power distribution was confirmed in the zero power CX reactor, Figure 1-13. The CX was a 19-element configuration that was neutronically representative of the design. Agreement between experimental results and analysis performed prior to the tests was extremely good, being within 0.5%. An equally impressive accomplishment was obtaining DOE approval: the CX was the first reactor approved for operation by the DOE in over 10 years.

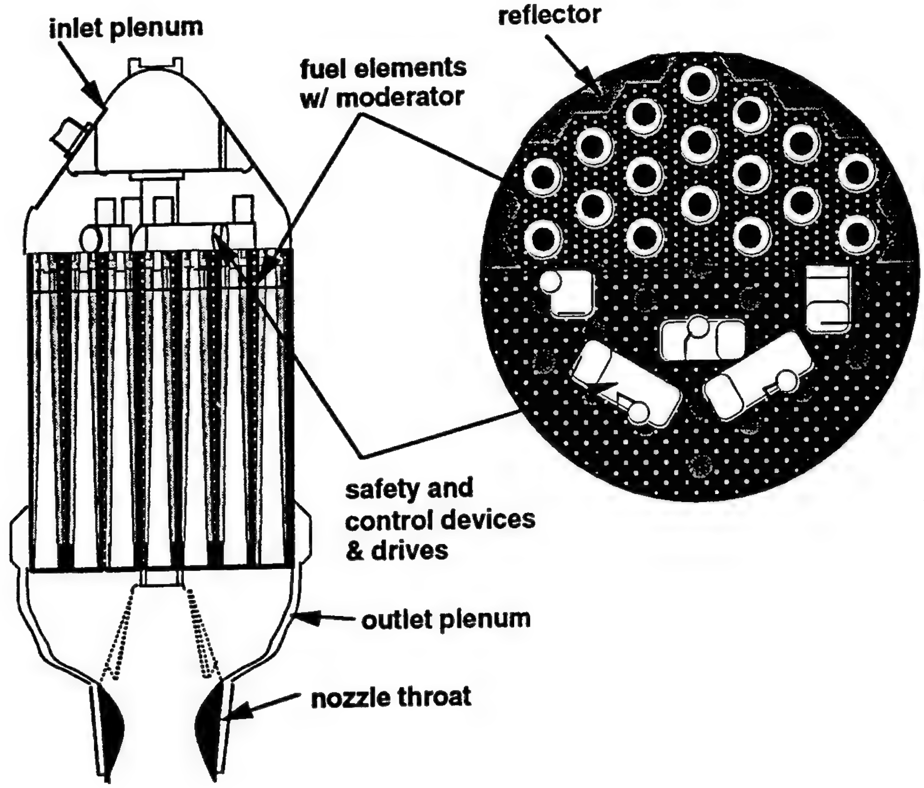


Figure 1-12 Typical Reactor Assembly

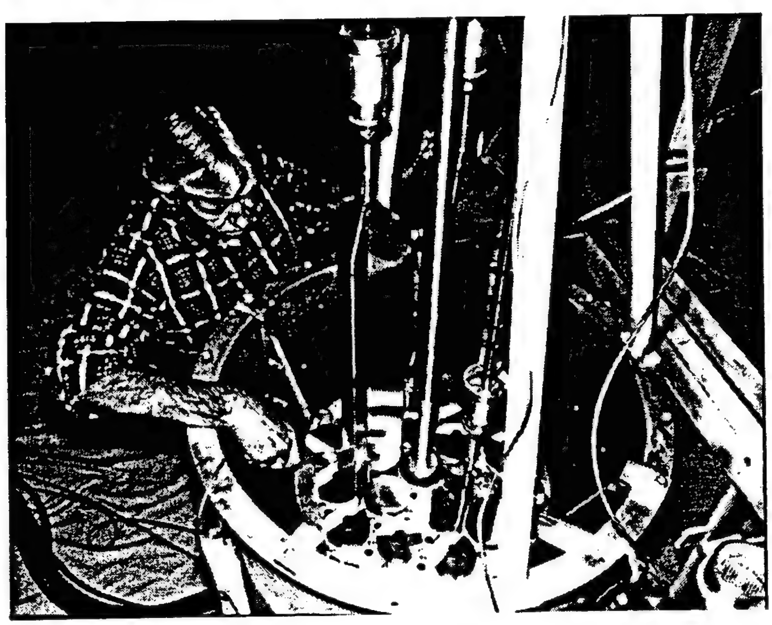


Figure 1-13 Critical Experiment Reactor

1.4.4 Balance-of-Plant

The non-nuclear balance-of-plant components received far less attention than did the reactor and its components. This was due to funding priorities to demonstrate the feasibility of the SNTP's particle bed reactor. Even with this reduced priority, significant progress was made in the development of a high-temperature turbopump, a radiation-cooled nozzle, and materials/coating technologies.

A high temperature (2750 K) turbine design was developed that allowed the direct feed of hot hydrogen, bled from the nozzle chamber, to the turbine. The turbine design featured carbon-carbon turbine wheels and static structure using a new ultra high modulus (UHM) fiber developed by the program. In addition to the design effort, which underwent an internal PDR prior to program termination, fabrication development was in progress. The status at the end of the program was that a viable process for fabricating the carbon-carbon rotor blank was partially demonstrated, using a non-prototypic fiber. The tooling was also being developed, and five graphite turbine wheels were machined, one of which is shown in Figure 1-14.

After a number of configurations were analyzed, an integral reactor pressure vessel and nozzle assembly was baselined for the SNTP engine. The design featured a filament wound carbon-carbon structure starting at the upper dome of the engine and extending to the throat region, as shown in Figure 1-15. Filament winding of carbon-carbon was demonstrated on

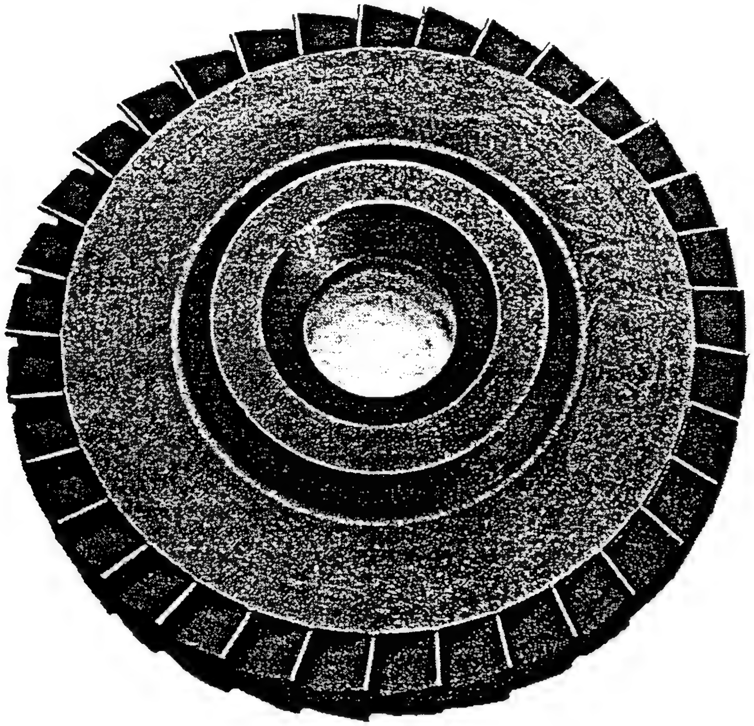


Figure 1-14 Graphite Turbine Wheel

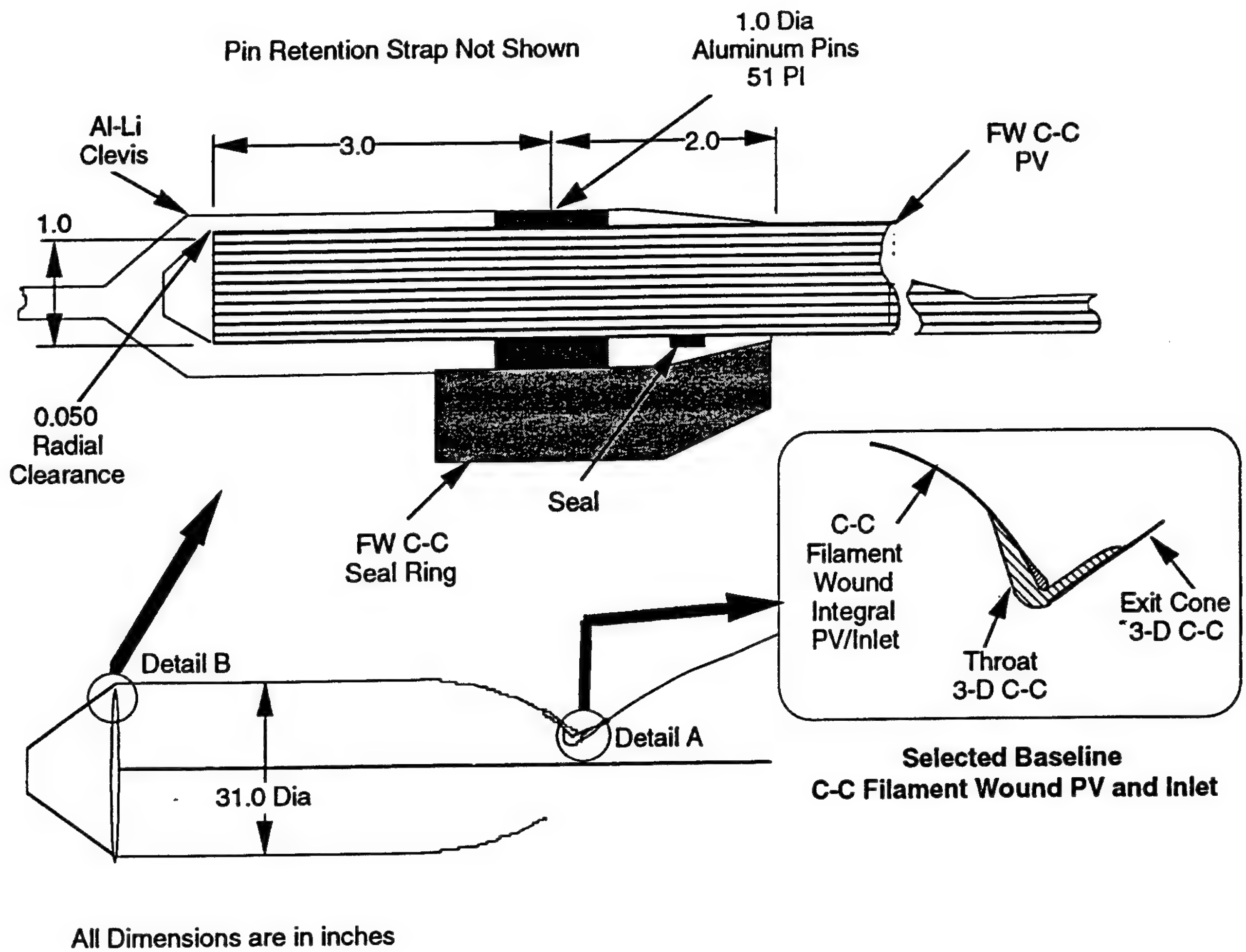


Figure 1-15 Pressure Vessel/Nozzle

small-scale cylinders but was yet to be proven on the full-scale assembly. Use of this material resulted in the best performance and lowest weight, and provided the largest structural margins. The latter is due to less nuclear heating of carbon materials than metallic materials, thereby reducing thermal stresses which were the primary design drivers.

The joint area between the pressure vessel and the aluminum-lithium upper dome received much design attention, and a functional design was completed. The joint configuration, shown in Figure 1-15 (Detail B), met the requirement for maintaining structural integrity and leak tightness throughout the entire range of thermal conditions from cold startup to operating temperature.

In addition to the development of the major components described above, the program recognized that development of certain technologies was essential to the successful development of the SNTP engine system. These technologies were common to several components, and combining the efforts resulted in efficient use of the available facilities and resources. Prime among the technologies was the materials and coating development efforts being performed by several of the SNTP organizations. Carbon-carbon was being developed by Hercules with an UHM fiber that exhibited 50% increase in strength, resulting in very efficient turbopump and nozzle designs. Coating work at BNL and Hercules (with coating houses, e.g, Union Carbide and Ultramet) resulted in carbide coatings to protect the carbon-

carbon components from the reactive hot hydrogen gas. Other technologies addressed were advanced instrumentation where in-situ measurement of component temperatures in the severe environment was beyond the state of the art, flow modeling to gain insight into the macro and micro effects in the fuel element, and integrated controls.

The task of successfully designing, building and testing a nuclear engine was indeed a daunting one. Technical challenges often paled in comparison to the effort required to maintain support and adequate funding for the program. Despite these drains on precious program resources, major accomplishments were achieved:

- Many missions were identified that were either enabled or enhanced by SNTP performance.

- An engine design was developed meeting safety criteria and providing robustness for multiple restarts while maintaining high performance: I_{sp} of 930 seconds, T/W of 20:1.

- Fuel, materials, and thermal-hydraulic issues had either been resolved or a clear path to resolution was established.

- A Final Environmental Impact Statement was completed and scoping meetings and public hearings were held within the regions of interest associated with candidate test sites: the Nevada Test Site and the Idaho National Engineering Laboratory. A Record of Decision (ROD) was pending at the time the SNTP Program was terminated.

- An economical step-wise approach to system development testing was in place that would have resulted in a ground demonstration test in the year 2000, with a total program cost that was estimated to be well below $1B (including $200M already expended).

- As an indication of the potential cost effectiveness of SNTP upper-stage propulsion, the savings on one (1) NASA mission (Pluto Flyby) would have paid-back the total remaining SNTP development cost. The basis of this estimate was replacing two (2) Titan IV launches with a single Atlas IIAS launch for a savings of approximately $600M. Other distant planet and asteroid missions (e.g., Pluto Orbit) would have been enabled by SNTP.

- A flight test concept was developed that would place the SNTP upper stage in a nuclear-safe orbit using an Atlas IIAS booster. The SNTP would be used to leave earth orbit and reach escape velocity. As part of the SNTP flight qualification a useful scientific payload could be carried to an outer planet.

Perhaps one of the most significant accomplishments of the SNTP program was the successful integration of the human resources from the government, national labs, and industry into a homogeneous, dedicated team with one objective -- to make the SNTP program a success.

2.0 INTRODUCTION

2.1 The Early Years

From the earliest days of the U.S. space program in the early/mid 50's and on into the early 70's, the nation moved rapidly forward in space exploration. In addition to launching larger and more complex unmanned spacecraft, a robust manned space program was being conducted that was highlighted when we successfully landed the first man on the moon in 1969. Throughout those years our space planners continued to lay out follow-on programs that included ever more exciting and demanding missions, supported by numerous technology programs to develop the needed hardware systems. Development of nuclear systems was very much a part of this national explosion in space technology.

The first nuclear systems to reach space were power systems. Most of these were radioisotope-thermoelectric-generator (RTG) systems that produced up to a few hundred watts of electric power. The one and only U.S. reactor system launched, SNAP-10A, was placed into orbit in 1965. The USSR space program launched several nuclear reactor systems for powering their RORSAT series of spacecraft. Unfortunately, the USSR policy of allowing operation of these systems in low earth orbit resulted in global concern about the use of nuclear systems in space when one of their systems (Cosmos 954) accidentally reentered over northern Canada in 1978.

Nuclear propulsion had long been recognized as essential for moving out and beyond the moon. One of the more ambitious missions on the drawing boards to follow the Apollo Program was a manned mission to Mars. A nuclear rocket development program, ROVER and later the Nuclear Engine Rocket Vehicle Application (NERVA), began in 1955. It was a hardware oriented program that included the testing of 19 reactors and engines. The program was well along the way of providing the U.S. with a nuclear propulsion capability when, in the late 60's and early 70's, our national economic priorities changed and space exploration ambitions were scaled back, including the manned mission to Mars. After 17 years of development, and without the pull of a firm mission, the NERVA Program was terminated in 1973 after expending $1.4B (then-year $).

Over the decade following the termination of the NERVA Program, the benefits of space nuclear systems continued to be considered and promoted by space technologists. Several different nuclear system concepts for space power and propulsion were conceived and studied, but little was spent on developing hardware. In 1983 things started to change. The newly formed Space Defense Initiative Organization (SDIO) began developing ideas for new, large, bold space missions that would benefit from nuclear systems. A nuclear power system development program, the SP-100 program, was initiated in February of 1983 and aimed at developing a 100 kW_e system. This decade-long program faced the same problem as the SNTP Program, that is a definite mission, and was terminated.

2.2 The Particle Bed Reactor Emerges

One of the more novel nuclear reactor concepts conceived during the 70's and early 80's was a gas cooled reactor invented by Dr. James Powell of BNL. Dr. Powell's concept, named

the Particle Bed Reactor (PBR), took its name from the fact that it utilized nuclear fuel in the form of particles about the size of grains of sand that were packed within two concentric, cylindrical, porous frits to form a fuel element. Several fuel elements would be assembled to form a reactor. A cold gas, such as hydrogen, would be passed radially through the fuel elements, cooling the reactor and heating the gas, and then expelled axially out through the inner hot frit. The fuel's very high surface area to volume ratio allowed a high heat removal efficiency with very high power densities, in a very compact, lightweight package that is ideal for space power and propulsion applications.

In 1982, Grumman received a briefing from Dr. Powell on his innovative PBR concept. Quickly recognizing that its unique characteristics of compact size, high power density, and very low weight made the PBR ideal for space power and propulsion systems, Grumman immediately committed personnel and resources to pursue the further development of Dr. Powell's PBR concept. Working closely with Dr. Powell, conceptual designs were formulated and analyzed which confirmed the aerospace utility of the PBR concept.

Over the next few years, Grumman began building a multi-organization team that provided the diverse talents and capabilities necessary to enhance and expand our conceptual studies. Initially, Garrett joined Grumman to pursue early Brayton Cycle power applications. Babcock & Wilcox was then invited to participate for their reactor and fuels experience. Later, Aerojet was enlisted to provide propulsion system component expertise.

Throughout those early years, a multitude of briefings were given to government agencies on a variety of PBR power and/or propulsion systems. In 1985 BNL and Xerad briefed the Air Force Space Division on a PBR-powered, ground-base, boost phase ICBM interceptor. In 1986, an Orbital Transfer Vehicle study contract was awarded to BNL and Grumman by the (then) Air Force Astronautics Laboratory to further define the benefits of a PBR propelled OTV. The results of the study efforts were so encouraging that experiments and tests were conducted to address and confirm some of the critical issues of the PBR concept.

In 1987 SDIO directly contracted for a ground-based, boost phase intercept Phase I program based on PBR technology. The program was given a Special Access Required (SAR) classification. The original concept was designed to catch Soviet SS18 ICBM's during their launch (boost) phase deep in Soviet territory. The interceptors were multi-stage (MX 1st stage, PBR powered 2nd stage, KKV upper stage) and forward launched, e.g., from bases on the northern edge of Alaska. This SDIO work led to a preliminary design of a rocket engine compatible for this application.

During the 1987-1989 time period, the Grumman-led industry team, working with SNL and BNL, performed a concept feasibility study and experiments that resolved issues of a PBR nuclear propulsion engine. The work included conceptual design work on a postulated strawman and included derivation of a baseline engine design. These studies convinced many from government and industry that an advanced PBR rocket engine could be developed to provide at least twice the performance of conventional rocket engines, with specific impulse approaching 1000 seconds and having thrust-to-weight ratios between 25 and 35 for thrust levels equal to and greater than 20,000 pounds.

One of these important experiments was the demonstration of the PBR thermal hydraulics in 1988 blowdown tests at BNL using electrically heated beds and process fluids such as helium and hydrogen. These tests verified that the particle bed fuel element was an efficient design that could provide the high rate of heat transfer necessary in high performance reactors. The power densities shown to be available with high flow rates of helium and hydrogen indicated that compact lightweight reactors could be designed.

In the later part of 1988 and into 1989, The Pulse Irradiation of a Particle Bed Fuel Element (PIPE) project was conducted to establish the feasibility of the fixed particle bed reactor fuel element assembly design for space power and propulsion applications. This first integrated testing of a PBR fuel element, designed and fabricated by B&W and tested in the ACRR at Sandia National Laboratory, was conducted in two series of tests: PIPE-I and PIPE-II. Although it was not possible, due to the ACRR operating capabilities, to achieve the full power densities and flow rates that would exist in an actual PBR, the tests did prove the feasibility of the PBR concept. Exhaust temperatures approached those necessary for an actual PBR rocket and the particle fuel performed as expected. Problems experienced during the PIPE-II series of experiments caused by carbon contamination of the test loop and manufacturing of the test element did not alter the overall success of the experiments.

The advances in modern computing capabilities and design codes that had been made since the days of NERVA were an important element in a cost effective development of the PBR system. In 1989 the first PBR ever built, the Critical Experiment (CX) reactor was tested at zero power at SNL. The CX reactor was the first test reactor to be approved for operation by DOE in over ten years. Test results compared very favorably with pre-test predictions and served to benchmark the PBR neutronic design codes.

During this same time frame, SDIO had developed missions that utilize megawatts of electrical power. The SP-100 system had been designed for $100kW_e$ using thermoelectric energy converters which do not convincingly extend into the megawatt region. Following a competition, an industry/national laboratory team consisting of Grumman (Prime Contractor), B&W, S^3/Maxwell Labs and BNL won a 10-month study effort, under contract to Idaho National Laboratory (INEL), to develop and document a preliminary design of a multi-megawatt space power system based on the particle bed reactor. Analytical and major hardware feasibility issues of fuel particle integrity, flow-to-power matching, and fuel element integrity were identified, and plans developed to resolve these issues. The team's Phase II proposal was selected to continue development; however, as a result of changing mission needs, funding was never allocated and the program was not implemented. The demise of the multi-megawatt program meant that continued PBR development would be focused on rocket engines.

From its early promotion in 1982 through 1989, the analytical and experimental evidence mounted that the PBR was a viable concept capable of providing the significant performance improvements needed for 21st century space missions. This collection of work had established the feasibility of the PBR concept and allowed the Program to proceed to Phase II, technology demonstration and validation.

2.3 The Program Transition to the Air Force

By the late 1980's peaceful co-existance began to develop between the U.S. and the Soviet Union, and the Program's objectives started to change from interceptors to space lift nuclear rocket missions. Mission studies continued to demonstrate that a PBR-powered upper stage would more than double the payload capabilities of the Delta, Atlas, and Titan class boosters, as well as NASA heavy lifters. Over the summer of 1989 a competition was conducted for a Phase II technology demonstration/validation program. At the start of FY '90, a newly structured team was selected and awarded a multi-year contract to ground- test demonstrate a PBR-based nuclear thermal propulsion system. Grumman was selected as the Prime/Integrating Contractor and B&W was awarded a sole-source Associate Contractor role for fuel and reactor hardware systems. The Sandia National Laboratories and Brookhaven National Laboratory rounded out the development team.

No sooner had the program gotten underway, when a Senate committee's concerns about the program surfaced in the FY '90 Appropriations Bill that required obtaining the endorsement of the three service Secretaries and the review and endorsement by a Defense Science Board (DSB). Until accomplished, program funding was severely limited. Technical progress was slowed over the fiscal year while efforts were directed to satisfying the Congressional language. By the end of FY '90, the program had obtained the endorsement of the three service secretaries and a Defense Science Board (DSB) task force had performed a comprehensive review of the program and found it to be technically sound with wide mission utility. The DSB recommended a national commitment to continued development of a PBR-based nuclear thermal propulsion system. A second DSB task force reviewed various nuclear propulsion options in May 1992 and concluded that the PBR was the preferred nuclear propulsion system for further development. In addition, they once again strongly encouraged continuation of the Program.

Somewhat in parallel, but slightly lagging the DSB reviews, NASA initiated a series of comprehensive reviews to evaluate the application of nuclear propulsion to future NASA missions, especially the Space Exploration Initiative (SEI). The NASA review team was assembled from representatives of NASA HQ, the various NASA centers, DOE and selected consultants. Their findings indicated that the PBR thermal propulsion approach was a viable, albeit higher risk, approach for their needs. Specifically, NASA concluded that the higher thrust-to-weight of the PBR engine was not required for the SEI mission.

The two DSBs and NASA findings were re-enforced when, under tasking by then Vice President Dan Quayle and the National Space Council, General Tom Stafford's Synthesis Group conducted a comprehensive study of the Space Exploration Initiative and found that nuclear thermal propulsion was a critical, enabling technology for manned missions to Mars. In a letter written to Admiral James Watson, then Secretary of DOE, General Stafford strongly endorsed the work of the Program and identified the PBR engine as the preferred approach for nuclear thermal propulsion.

In anticipation of an expansion and acceleration in the Program, it was transferred to and placed under the management of the Air Force Phillips Laboratory at the beginning of FY '91, and was named the Space Nuclear Thermal Propulsion (SNTP) Program. In January

of 1992, at the annual Space Nuclear Power and Propulsion Symposium in Albuquerque, at a highly publicized press conference, a formal announcement was made by Senator Pete Domenici (NM) and Colonel Marchiando, CO of Phillips Lab, that our nation was proceeding forward with the development of a PBR-based nuclear rocket engine.

After the media attention subsided, there were immediate indications that the Air Force was considering terminating the program. Program progress was slowed throughout the remainder of 1992 while different options were considered. No funding was requested by the Air Force for the program in the FY '94 budget and the sizable FY '93 funding that had been appropriated for exclusive use by the SNTP program was withheld pending program transfer to another agency or termination. The SNTP Program was dealt its death blow when the FY '94 Appropriations Bill (November 1993) transferred the FY '93 funding to another program, and the SNTP program was finally terminated in January 1994.

3.0 SNTP PROGRAM SUMMARY

3.1 Program Objective and Goals

From its inception the SNTP Program was approached from a systems engineering point of view by considering it as a multi-phase program that would culminate, after several phases, in providing a flight-proven nuclear rocket engine for an operational system. Based on the history of previous new technology programs, it was well understood that the development of a nuclear thermal rocket engine would be very tightly coupled to mission "pull", rather than any technology "push." Maintaining a focus on total nuclear engine system design and performance, traceable to a flight engine, would be needed to maintain user support. Early in the program, analyses of potential mission applications were conducted and a wide range of engine system design and performance requirements derived. Technology assessment studies were conducted for various sets of mission design and performance requirements. These studies indicated that there were a few missions that would benefit from a propulsion system with a specific impulse (I_{sp}) of about 700-800 seconds. This level of performance represented a significant improvement over conventional rocket engines and could be achieved quickly, with low risk and cost using existing or near term technology. On the other hand, many missions were identified that would greatly benefit, and in some cases be enabled, by a system with an I_{sp} of 1000 seconds, more than double that of a chemical rocket engine. This major step in performance would require a more aggressive, higher risk and cost program that would require more significant technology advancements. After considerable analysis and debate as to what would make the most viable, "sellable" program with strong user support, and would provide maximum return to the U.S. for its investment, it was decided that the more aggressive program requiring some significant technology advances would be undertaken.

The program underwent a complete change in scope and objectives from its inception as a single mission SDIO program in Phase I to an Air Force technology demonstration program at termination. The Phase I objective was to demonstrate the feasibility and design of a PBR nuclear rocket powered interceptor. In the initial stages of Phase II, still under SDIO control, the mission utility was broadened. Interceptor missions were deemphasized and second stage applications for placing payloads in earth orbit or into deep space were targeted. After the Air Force took control of the program at the start of FY '92, the program was restructured as a technology demonstration program with an engine configuration that would be traceable to a flight engine. The program priorities were also revised, with lower program risk replacing aggressive performance enhancement. At that time the Air Force program was renamed the Space Nuclear Thermal Propulsion (SNTP) Program.

3.2 Program Approach

Phase II of the program was to include all design and development efforts leading to and including a complete engine system ground test demonstration traceable to a flight engine. It was to address and resolve the technology development issues and implement the efforts required to build the components required for the demonstration. Limitations on resources may have precluded demonstrating the actual level of technology necessary for a flight engine, in which case, the technology would have been separately demonstrated to allow a smooth

transition to the next phase of engine development. For example, the fuel used in the development engine would be selected on the basis of development lead times and interim test need dates, whereas the fuel selected for the flight engine would have higher performance characteristics. In this case the higher performance fuel could be pursued at the appropriate level to demonstrate its performance characteristics and fabricability, in time to be available for the next phase of the program.

The general approach to the program is shown in Figure 3.2-1. Ultimate flight engine design and performance requirements based on a postulated design reference mission were developed and used as a framework for the development program. Flight engine performance requirements were derived from the reference mission and engine subsystems, subassemblies, and component designs developed. The demonstration engine requirements were then to be developed so that traceability to the flight engine would be maintained. Specific ground test and safety requirements would be incorporated into the demonstration engine design.

Testing was a major effort on the program. A cost effective, low risk philosophy of testing at the component (or part) level and building up to more complex and higher fidelity subassemblies was being followed. Testing was complemented by laboratory simulations which verify electronic interfaces and computer software, and engine integration tests.

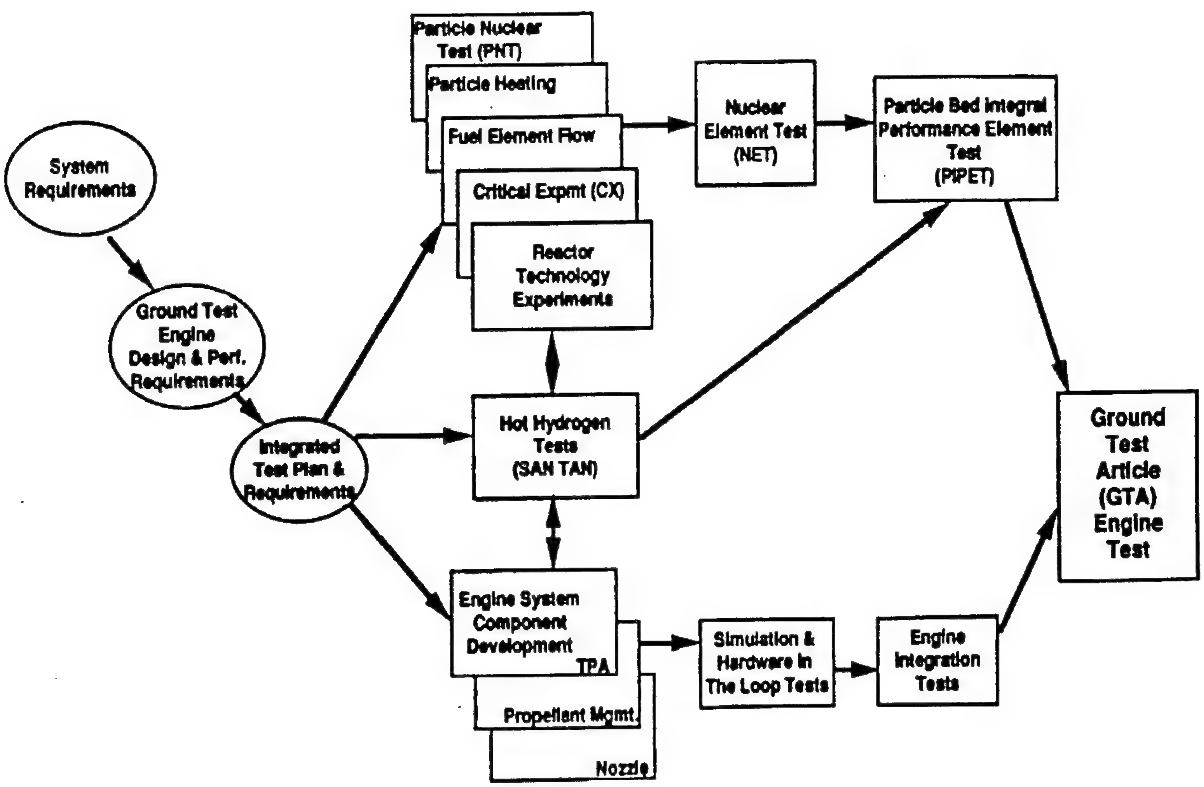


Figure 3.2-1 Program General Approach

As shown in Figure 3.2-1, the reactor technology development started with a series of experiments that provided valuable data to the reactor experimenters and designers. The Critical Experiment (CX) tests were performed by a team at SNL in late 1989 through mid-1991, to obtain the experimental results used to verify the reactor neutronic design and to benchmark the transport codes used to design PBR reactor. Second generation Critical Experiments were planned to provide higher fidelity testing to support the design of the demonstration engine.

After confidence was established in the reactor element design, the testing progressed to higher levels of assembly. Single fuel element testing, the Nuclear Element Test (NET), was performed in the SNL ACRR under a range of conditions to characterize and validate the design. The first several NET's were designed to validate the PBR fuel element concept, obtain engineering data for design purposes, and to benchmark codes. The fuel, size, and materials configurations in each NET series were not to be the same as the demonstration engine element, but were to address specific design issues. The final series of NET 's were going to test a fuel element that was as close as possible to the demonstration fuel element.

Once the fuel element design was validated in the NET's, fuel elements were to be tested in a self-contained critical assembly known as the Particle Bed Reactor Integral Performance Tester (PIPET). The PIPET tests would have provided, for the first time, operation of the PBR elements at prototypical operating conditions. These tests were to be performed at a Nuclear Ground Test Facility at the Saddle Mountain Test Station (SMTS) on the Nevada Test Site or the Idaho National Engineering Laboratory (INEL), pending issuance of a Record of Decision (ROD) following the National Environmental Policy Act (NEPA) of 1969.

Several PIPET campaigns were planned. The tests would have started with bare, prototypic fuel elements tested at operating conditions in the PIPET driver assembly, progressed to moderated fuel elements, and then to a core assembly. These test articles would have demonstrated the reactor core configuration and design.

Following a successful PIPET campaign, reactor testing would have stepped up to the engine system level. In support of the engine ground test, the demonstration engine (DE) would have integrated selective, concurrently developed, prototypical engine system hardware components designed for the ground test environment. The DE was to be tested at the Nuclear Ground Test Facility, and if successful, would have achieved the Phase II objective of ground test demonstrating and validating the PBR engine technology and capabilities. Throughout the program, traceability to flight engine designs was to be maintained. Successful completion of Phase II of the program would have enabled Phase III for ground flight engine qualification, a flight demonstration, production, and deployment.

3.3 Programmatics

By the beginning of Phase II of the program, a multi-discipline, multi-organization team had been assembled that included participants from government agencies, national laboratories, and industrial contractors. The Air Force's Phillips Laboratory was the responsible government institution and provided program control and administration from the SNTP Program Office (PL/VT-X). The principals in the development team included:

Grumman, the Prime Contractor / System Integrator; Babcock & Wilcox, the reactor and fuel supplier; Brookhaven National Laboratory, reactor neutronic analysis and configuration definition; and Sandia National Laboratories, test facility, in-core testing, safety and environmenal analysis. Xerad Corp. assisted the SNTP Program Office with technical and management oversight as the SETA contractor. The overall contractual/supporting organizational structure is depicted in Figure 3.3-1 and includes the several other government agencies and subcontractors that completed the team. Just prior to program termination, the team was about to be expanded to include international participation. Grumman had completed negotiations and a subcontract was ready to be signed with the Russian Scientific and Industrial Association NPO Lutch for advanced nuclear fuel and materials technology.

During Phase I and the initial stages of Phase II, the SDIO program was conducted in a fast-track, streamlined fashion where emphasizing rapid resolution of basic design and technology issues associated with development of a high temperature, high power density, advanced technology version of the PBR engine. The organization of the program during this period was dynamic and structured to rapidly change direction as the baseline engine design requirements evolved and development issues were resolved. The concept of working groups was employed with each staffed by technical experts from across the team organizations. The working groups were essentially horizontally structured, with strong direction and control provided by the SDIO Program Manager, Lt. Colonel Roger X. Lenard. Team communications was primarily accomplished using a presentation format at regularly held program meetings, where resolution of issues and design decisions were usually done in real time. Overall

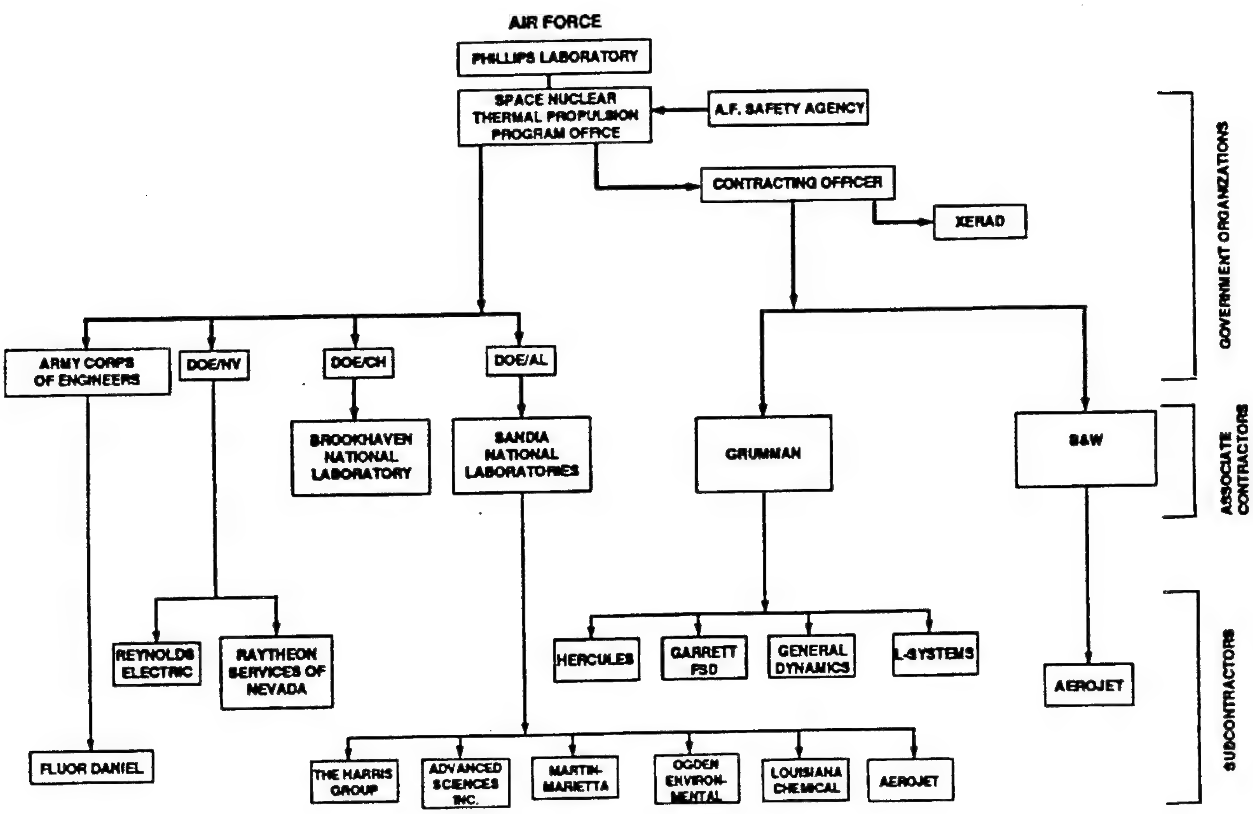


Figure 3.3-1 SNTP Contract Structure

integration of the various activities was essentially performed and controlled by the program executive committee led by the Program Manager. This management approach worked relatively well for the early stages of the program and allowed rapid progress by providing the flexibility to quickly adjust program direction in response to changing program priorities/ problems. The close working relationships established between all the program personnel within the working groups and at these meetings helped to minimize normal inter-organization barriers and did much to promote and establish a strong total team spirit that focused on the program objectives. However, as the program grew and matured, the size of the regular program meetings became unwieldy and it became desirable and even necessary to adapt a more formal and classical management approach. Following the rotation of the original Air Force Program Manager, the new AF Program Manager initiated the restructuring and formalizing of the Program, in preparation for its transition to the USAF.

In the new organization, a well staffed PL Program Office (PL/VT-X) was created to monitor and direct the contractor organization. The contractor team was organized into a management structure that amalgamated the national laboratories, industrial contractors, and subcontractors into an integrated SNTP organization reporting to the PL SNTP Program Office. This new integrated organization, shown in Figure 3.3-2, was headed by Grumman, the SNTP Prime Contractor/ System Integrator, and incorporated personnel from participating organizations in key positions of responsibility. It drew upon the concepts of concurrent engineering/task teaming to perform work that aligned with a newly created Work Breakdown Structure (WBS). The integrated organization featured a strong system integration/ system engineering function and provided PL/VT-X with a single-point-of-contact interface with the contractor team via the Prime Contractor.

3.4 Work Breakdown Structure

The overall integrated program Work Breakdown Structure (WBS) evolved over the life of the program into a program unique, streamlined organization of work, applicable to all participating organizations, that provided a framework upon which all programmatic technical, schedule, and cost control was accomplished. The latest WBS, shown in Figure 3.4-1 , had been tailored to meet the needs, and complement the integrated management organization discussed above. It reflects the technology demonstration nature of the program, and serves as the outline for detailed technical discussions in the later Section 4.0.

3.5 Program Master Schedule

Establishing a Master Program Schedule (MPS) was an elusive goal that was never totally achieved. Program annual funding never reached a stable enough state where a detailed multi-year, overall MPS could be generated, finalized and followed. Instead, summary MPSs were generated to maintain long range focus on program goals and used as a basis for detailed annual schedules and work scope planning based on in-hand, yearly appropriated program funds. Figure 3.5-1 presents one of the last summary schedules for the program and was based upon achieving a ground test demonstration of a flight traceable engine system by the year 2000.

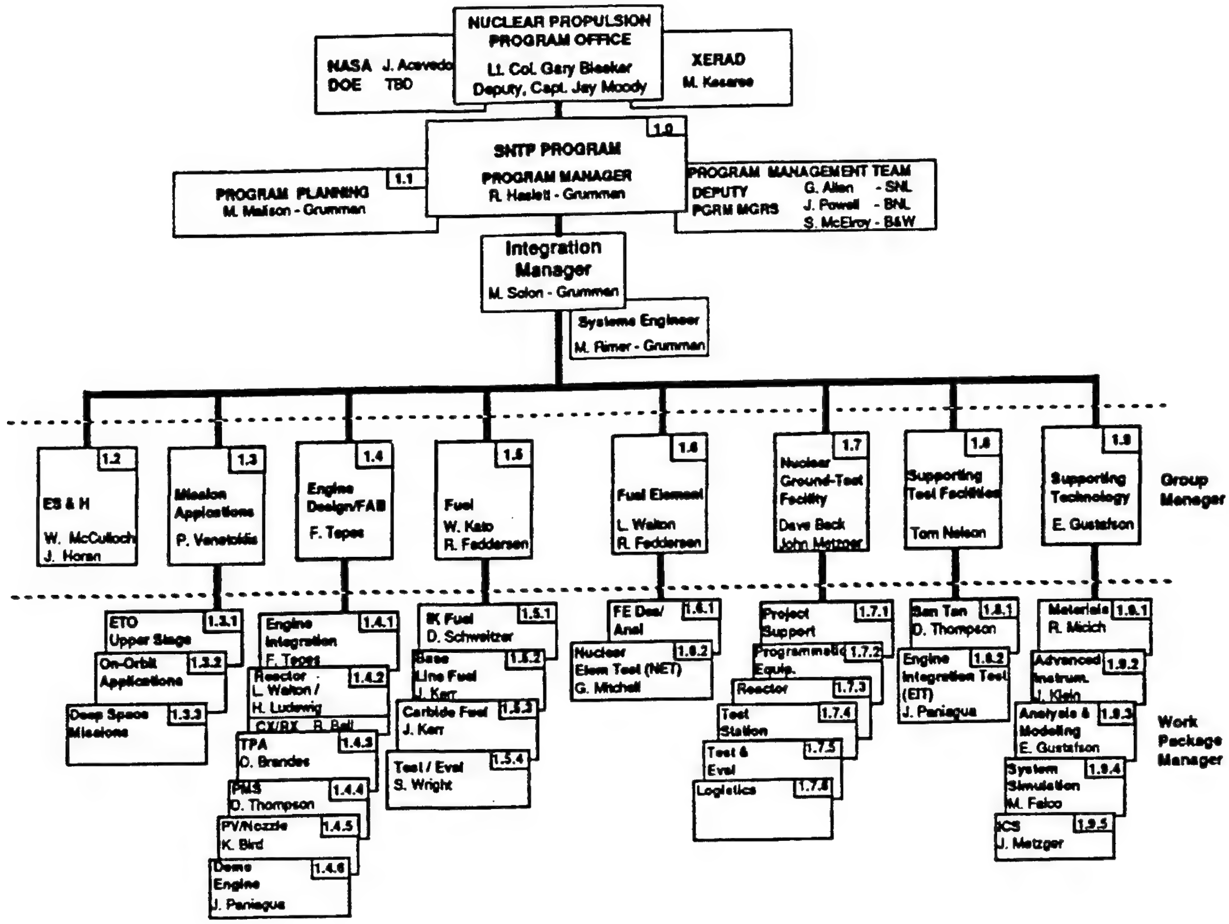


Figure 3.3-2 Integrated SNTP Organization

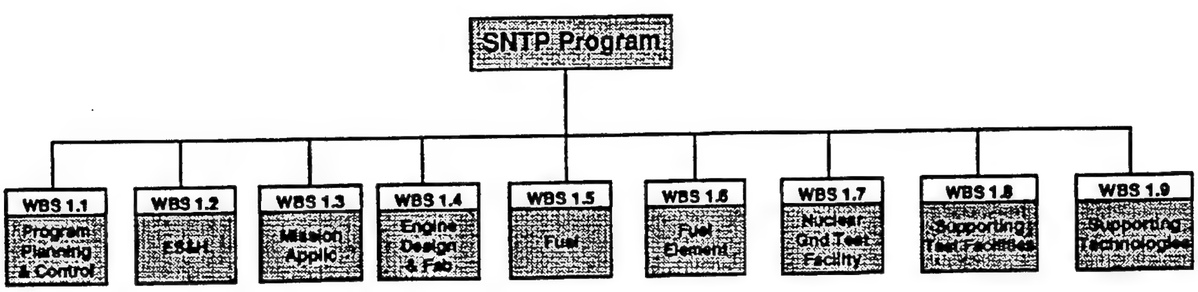
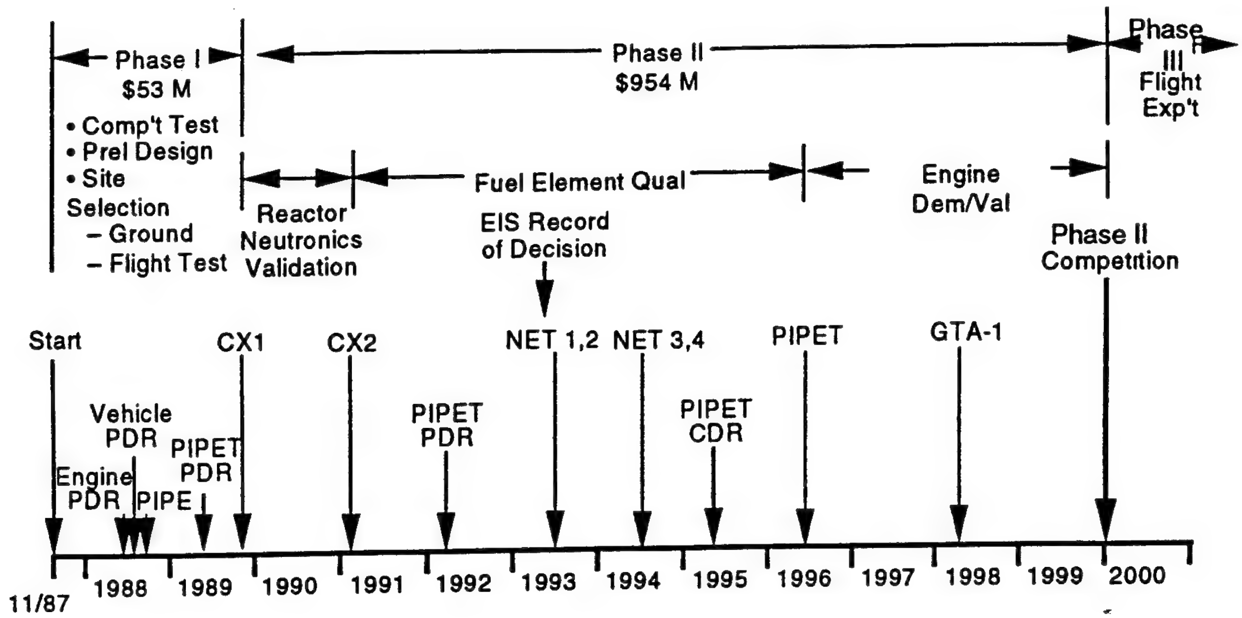


Fig. 3.4-1 – SNTP Summary Work Breakdown Structure



GTA - Full Scale Ground Test Engine

CX - Critical Experiment at Sandia

NET - Fuel Element Test in Sandia Reactor (ACRR)

PIPET - Fuel Element Qualification Test in Be - Moderated Reactor (NTS)

Figure 3.5-1 Program Master Schedule

3.6 Program Costs

The total cost of developing a space nuclear thermal propulsion system is highly dependent on several cost drivers that were all considered in formulating the SNTP Program approach: the required/desired performance levels of the engine and the extent of the technology advancement required to achieve that performance; the approach to program management, i.e. fast-track, streamlined vs. formal, methodical; and the approach to the test program. Cost estimates that considered these and other variables had resulted in total Phase II cost projections that ranged from as low as $500M to over $1.2B for the more comprehensive program. The baseline SNTP Program, at last estimate, was projected to have a total cost of about $900M, including the $200M spent through FY93. However, several cost reduction steps had been identified and were being considered that may have significantly reduced the total program cost.

Establishing a baseline program was an evolutionary process. Early in Phase II, mission/engine/technology trade studies were conducted that concluded that a high performance engine system requiring some significant, but "doable," advancements in materials and engine component technologies would have added several 10's of millions of dollars to the overall program cost, but the added cost would have provided maximum benefit and payback to the nation.

Early in the program, pressing mission needs required a fast-track, streamlined approach to the program, and although risky, would provide an operational system in only a few years. This fast-track approach, barring any major setbacks, actually would have saved millions of dollars versus a longer program, but would have increased the annual funding requirements to well over $100M per year. As the urgency of the original primary mission subsided, the program was slowed/extended and a less risky, more deliberate and methodical approach adopted.

By far the most significant cost driver for the program was the test program. The ROVER/ NERVA Program, with over $1.4B (then-year dollars) spent, had been an expensive program due in large part to the decision to ground test complete systems. If modern environmental regulations and constraints had been imposed on that program, program costs probably would have more than doubled, and perhaps tripled. The SNTP Program considered various test program approaches that ranged from a high risk, straight to a flight test, to a more conventional ground test qualification program. After much analysis and finally with the recommendation of a Defense Science Board, it was decided that the most cost-effective approach to the test program would be to use a methodical, stepped test program where key system elements would be proven at the lowest possible level of assembly, gradually building up to a full system level ground test demonstration, to be probably followed by a flight test demonstration phase. Maximum use would be made of modern system simulation techniques and non-nuclear and nuclear element testing in existing test facilities before moving up in scale and complexity to total engine system nuclear tests. A cost effective test program element that was being considered just before the program was terminated was to perform limited fuel testing at an existing Former Soviet Union test facility. This idea never received a complete assessment and cost savings were never quantified. The SNTP approach to testing had the clear benefit of minimizing the cost and risk of each individual test by using mostly previously proven components and would have provided the knowledge base and confidence to reduce subsequent test anomalies.

The ground test of a full PBR engine system, because of the very high temperatures and power densities of the PBR, precluded using any existing national test facilities. Several ground test facility design options were considered, and it was finally concluded that a new facility located at the Nevada Test Site (NTS) would be required. This new facility would allow safe and environmentally clean nuclear testing of a limited quantity of restricted size engine systems. In spite of all efforts to design and construct a low cost test facility, the cost of environmental protection systems eventually increased the facility cost to about $500M, which represented about half of the total program cost. During the final year of the SNTP Program, a significantly lower cost test facility approach was considered that made use of underground weapons test tunnels located at the Nevada Test Site, that might be available due to nuclear weapons test ban treaty provisions. Use of these existing facilities never received a full design review, however, preliminary estimates indicated this approach could have reduced test program costs to approximately half of the baseline approach.

4.0 TECHNICAL DISCUSSION

4.1 Preface

The technical challenge facing the SNTP development team was to develop and ground demonstrate / validate a particle bed reactor engine design. The design goal was to develop a 20,000-80,000 pound thrust engine with a specific impulse of 1,000 seconds and a 35-to-1 thrust -to-weight ratio. This engine design goal would require technology advancements in several key areas including advanced high temperature and hydrogen-resistant materials for the PBR nuclear fuel and other reactor/engine elements, lightweight, advanced high performance propellant management components such as turbopumps, valves, etc., and new instrumentation and controls. These advancements would encompass and establish new design, analysis, simulation and testing, and manufacturing techniques. The challenge was accepted by the diverse multi-organization SNTP team, who made significant and impressive technical progress that added to the national data base and established a solid foundation for any future nuclear system development program.

In the following sections, the Work Breakdown Structure (WBS), Figure 3.3-2, is used as a framework for discussion of the specific technical activities and accomplishments of the program. The WBS used here was that put in place after the program was transferred to the AF, and reflects the program's refocus on technology demonstration. WBS 1.0, Program Management, being non-technical in nature, is not addressed in this section.

4.2 WBS 1.2 Environment, Safety and Health

4.2.1 Overview

The environmental, safety and health (ES&H) issues facing any new, modern technology program, and particularly a nuclear program can be immense. The SNTP Program recognized right from the start that stringent ES&H requirements would be imposed and the program would be subjected to not only detailed reviews and careful monitoring by technically competent personnel, but also be subject to public scrutiny. It was with this understanding that a dedicated group of scientists and engineers from across the SNTP team, led by SNL, were charged and made responsible for assuring that all ES&H issues received due consideration and that all requirements were met.

ES&H may be considered as being comprised of three subelements:

- Program Safety
- Safety Analysis and Documentation
- Mission Safety Analysis

During the ground test phases of the SNTP Program, responsibility included the identification of ES&H issues, development of ES&H related system design constraints and operational requirements, and the provision of such documentation that would be required to assure that test facilities and test articles can be designed, constructed, operated, and decommissioned in a safe and environmentally responsible way. It should be noted that those

activities directly related to the development of safety analysis reports (SARs) for the ground test facility was funded and managed as part of WBS 1.7. WBS 1.2 did have the responsibility for the ES&H evaluations and other activities required to present the overall SNTP Program as safe and environmentally responsible. In addition, ES&H had the responsibility for mission safety analyses, i.e., the assessment of the safety and environmental issues associated with the demonstration and application of the particle bed technology to space nuclear thermal propulsion.

4.2.2 Accomplishments

The major accomplishments of WBS 1.2 were (1) the preparation of an Environmental Impact Statement (EIS), (2) the preparation of the Program Safety Policy Document, (3) the definition of Program Safety Goals, (4) the development of a Management and Responsibilities Structure for Safety, and (5) identification of the safety issues related to a flight demonstration and deployment of SNTP systems.

Environmental Impact Statement

The EIS analyzed the potential environmental consequences of implementing a proposal to perform testing associated with the SNTP program. It complied with provisions of the National Environmental Policy Act (NEPA), which require preparation of an EIS and provided information to the decision makers and the public on the potential environmental impacts that could result from proceeding with development of the PBR propulsion technology through validation testing. The DOE was a cooperating agency in its preparation.

The Proposed Action that the EIS addressed consisted of the development and testing of the engine and propellant management system components (PMS) and assemblies, and construction and operation of validation testing facilities.

A series of tests would be performed, leading to the validation of the concept. Tests would be sequenced to begin with testing of multiple assemblies to demonstrate reactor fuel element operation, progress through tests to demonstrate the PMS, and culminate in testing a series of up to ten reactors that would gradually approach the desired performance conditions. Each test sequence would undergo a comprehensive safety analysis in accordance with DOE procedures for preliminary and final Safety Analysis Reports. Testing would be conducted in strict compliance with all applicable safety and environmental regulations and standards.

Two alternative PBR validation test sites were considered as part of the Proposed Action:

- Construction and operation of the PBR validation test facilities at the Saddle Mountain Test Station (SMTS) at the Nevada Test Site (NTS) The NTS is a DOE installation located in southern Nevada. Development of the facilities would involve construction on approximately 100 acres at SMTS. Infrastructure improvements would be required.

- Renovation of existing facilities and construction of some new facilities at the Contained Test Facility (CTF) at the Idaho National Engineering Laboratory (INEL). The INEL is a DOE installation located in east-central Idaho. Development of the PBR validation test facilities would involve the renovation of existing facilities on approximately 55 acres of developed land plus additional acreage for construction of the remaining needed facilities. The total developed area would be approximately 100 acres.

The No-Action Alternative would result in not carrying out the development and validation process for the PBR propulsion technology.

The scoping period began when the Notice of Intent to prepare an EIS for the SNTP program was published in the *Federal Register* on March 13, 1992. Issues were identified in scoping meetings held in Las Vegas, Nevada (April 7, 1992); Idaho Falls, Idaho (April 9, 1992); St. George, Utah (April 16, 1992); and Salt Lake City, Utah (April 22, 1992). The comments and concerns expressed at the scoping meetings and received during the public comment period determined the scope and direction of studies and analyses required to accomplish the EIS.

The EIS discussed the potential environmental impacts associated with implementation of the Proposed Action and its siting alternatives. To provide the context in which potential environmental impacts may occur at the two candidate field test locations and the surrounding communities, existing conditions and potential changes as a result of construction and test activities were described. Impacts to the physical and natural environment were evaluated for infrastructure, land use, transportation, hazardous materials/waste management, air quality, biological resources, cultural resources, geology and soils, noise, water resources, and health and safety.

The EIS considered testing options at SMTS or CTF. Influencing factors include projections based on program requirements that would likely influence the community setting, biophysical environment, and the health and safety of the supporting staff and the population of the surrounding communities. The influencing factors are summarized below and in Figure 4.2-1 for the three options considered: (1) Implementing the Proposed Action at SMTS, (2) Implementing the Proposed Action at CTF, and (3) No-Action.

Implementing the Proposed Action at SMTS

<u>Community Setting</u>

The community region of influence for the SMTS includes Nye and Clark counties, Nevada, including the city of Las Vegas. Peak construction requires a maximum of 100 personnel resulting in a negligible effect on population, local economy, and support service availability.

A new power line within the NTS power grid would be required; however, there is sufficient power at NTS to support this line. Solid waste, water supply, and wastewater consumption would represent a small increase in the total requirements, given existing capacities and past consumption levels.

No land use conflicts were anticipated. The testing activities would be consistent with the type of research conducted at NTS. No impacts to the Yucca Mountain Waste Repository were expected.

Traffic due to the Proposed Action being implemented at SMTS would result in a small increase on the main route connecting NTS to Las Vegas (U.S. 95). No adverse effects were expected.

Biophysical Environment

Transportation of hazardous materials (both radioactive and nonradioactive) would comply with all applicable regulations, and no impacts were expected. Storage and use of hazardous materials would be consistent with current operations at NTS.

Nonradioactive and radioactive hazardous wastes would be disposed of in existing disposal facilities. Facilities had sufficient capacity to support the SNTP program.

The hydrogen flare stack ignition system may cause very small quantities of carbon monoxide, nitrogen dioxide, and particulate matter. These emissions were not expected to add substantially to the regional air pollution inventory.

The loss of up to approximately 100 acres of low quality vegetation would result and approximately 1,000 Joshua trees would be removed. Minimal wildlife impacts would be expected.

No adverse impacts to archaeological, historical, Native American, paleontological resources, geology, topography, or soils were expected.

Health and Safety

Radiological hazards associated with normal and accidental reactor test operations and radioactive material transportation were evaluated. Three types of planned operations using two different sized reactor cores were identified. PIPET would constitute the first self-sustained power-producing test of multiple PBR element assemblies; GTA would involve testing a complete PBR core to gradually approach desired system performance conditions. Planned operations corresponded to low-power and full-power testing of the PIPET core, beyond full-power testing of this reactor, and both low and full-power tests using the larger GTA. Potential radiological releases were analyzed for all planned operational scenarios.

Modeling of potential radiological impacts was performed for the maximum case year. Results showed less than 1 percent of the environmental radiation dose in the NTS vicinity, and were well below both regulatory limits (U.S. Environmental Protection Agency [EPA] emission standards) and the SNTP program goal of no more than 20 percent of applicable regulatory limits.

Accident situations were also evaluated and a complete analysis performed for the

identified maximum impact case: a release of a significant fraction of a PIPET core fission product inventory during weather conditions corresponding to maximum credible impacts. The maximally exposed individual (MEI) would be well below accident-case siting guidelines.

Implementing the Proposed Action at CTF

Community Setting

The community region of influence for the CTF includes those portions of a six-county area (Bannock, Bingham, Bonneville, Butte, Jefferson, and Madison counties) within 50 miles, including Idaho Falls. Peak construction requires a maximum of 100 construction personnel. Negligible effects on population, local economy, and support service availability would result.

Electricity, solid waste, wastewater, and water supply consumption would represent only small increases in the total requirement, given existing capacities and past consumption levels. No land use conflicts were anticipated due to the nature of research activities at INEL.

There would be a small increase on roads accessing CTF. Traffic on public roads traversing the INEL may have to be rerouted during and immediately after some test operations. No adverse effects were expected.

Biophysical Environment

Transportation of hazardous materials (both radioactive and non-radioactive) would comply with all applicable regulations, and no impacts are expected. Storage and use of hazardous materials would be consistent with current operations at INEL.

No air quality impacts were expected from PBR test exhausts.

There would be a loss of approximately 50 acres of previously disturbed, low quality vegetation. The existing containment structure at CTF is potentially eligible for the National Register of Historic Places; possible adverse impacts would have been mitigated through consultation with the State Historic Preservation Officer. No adverse impacts to archaeological, Native American, or paleontological resources were expected.

No adverse impacts to geology, topography, or soils were expected. The natural topography near the site may be subjected to flooding; however, the CTF elevation has been raised 15 feet in the past to keep the site from being flooded in the case of failure of upstream flood control structures.

No noise impacts to non-project personnel or sensitive receptors were expected. Project personnel would comply with Occupational Safety and Health Administration noise limits and preventative/protective measures. Local wildlife would experience occasional temporary startle/fright effects. No water quality or surface water impacts were expected.

Health and Safety

Radiological hazards associated with normal and accidental reactor test operations and radioactive material transportation were evaluated. Three types of planned operations using two different sized reactor cores were identified. Modeling was performed for the maximum-case year (the largest numbers of operations in a single year) and the proposed test program lifetime. Results showed less than 1 percent of environmental radiation dose in the INEL vicinity, and well below both regulatory limits (U.S. EPA emission standards) and the SNTP program goal . Potential impacts of the test program were found to be extremely low relative to statistically expected occurrences of cancer fatalities and newborn genetic defects in the population of interest.

Accident situations were also evaluated and a complete analysis performed for the identified maximum-impact case: a release of a significant fraction of a PIPET core fission product inventory during atmospheric conditions corresponding to maximum credible impacts. Results indicated that the total dose to the MEI would be well below accident-case allowable exposures. The total increase in cancer fatalities and newborn genetic defect rates due to a maximum-case accident would be extremely low relative to the expected occurrences in the population of interest.

No-Action Alternative

Under the No-Action Alternative, the Air Force would not proceed with PBR technology development and validation. Other unrelated current activities at NTS and INEL would continue. No construction of new facilities would occur at SMTS, and no modification or construction of facilities would occur at the CTF.

Because none of these activities would take place, no impacts beyond those occurring as a result of other current or future programs or activities would result. No effects would occur in any of the influencing factors or biophysical resource areas.

Safety Policy Document

The overall ES&H objectives and guidance for the SNTP Program was provided in a Safety Policy Document, which was approved by the SNTP Program Office in May 1992.

The purposes of the Project Safety Policy were to establish the overall safety strategy envisioned for the SNTP program, to define the safety policy and the safety goals, and to define a framework for the implementation of this strategy. The objective was to ensure the maximum protection of the health and safety of the public and the SNTP workers, and to protect the environment from contamination or damage as a consequence of SNTP activities.

Implementation of the safety strategy was to be accomplished through the development of the various environmental, safety, and health plans and guidelines that were used in monitoring and controlling the SNTP activities. These documents include Safety Implementation Plans (SIPs), Environmental Assessments (EAs), Environmental Impact Statements (EISs), Safety Assessments (SAs), and Safety Analysis Reports (SARs).

	Proposed Action SMTS	Proposed Action CTF	No-Action
Local Community			
Land Use	No impact	No impact	No impact
Population	263; less than 0.04% increase	263; less than 0.2% increase	No impact
Employment	100 personnel; 2% increase	100 personnel; less than 1% increase	No impact
Transportation	Maximum of 5.9% increase in AADT	Maximum of 6.1% increase in AADT	No impact
Utilities			
Water	Less than 0.5% increase in withdrawal	Less than 0.1% of allocation	No impact
Electrical	New distribution line to the site required; 0.75 MW peak power requirement	Less than 1% of existing capacity required	No impact
Wastewater	2400 gal/day: septic system/leachfield to be constructed	2400 gal/day: < 1% of existing capcity to be used	
Solid Waste	Less than 1% increase	Existing and proposed new landfill sites contain sufficient cap. for solid wastes	No impact
Hazardous Materials/ Waste Materials	Shipment of less than 220 pounds of U-235 per year (part of component assemblies)	Shipment of less than 220 pounds of U-235 U-235 per year (part of component assys)	No impact
Waste	Less than 2% increase per year	Less than 1% increase per year	No impact
CERCLA	No impact	No impact	No impact
Radioactive Materials	Approx. 18% of existing capacity for disposal of low-level solid waste required. Ultimate disposal of TRU Waste is dependent on future opening of WIPP or another facility.	Approximately 46% of existing capacity for disposal of low-level solid waste req'd; disposal of LLW with TRU greater than 10 nanocuries per gram is unknown. Ultimate disposal of TRU waste dependant on future opening of WIPP or another facility.	
Natural Environment			
Air Quality	Slight increases in PM_{10} emissions and emissions from construction and worker vehicles. No impact on air basin attainment.	Slight increases in PMI_{10} emissions and emissions from construction & worker vehicles. No impact on air basin attainment	No impact
Biological Resources	Up to 1,000 Joshua trees impacted by construction; temporary impacts to wildlife due to noise; no impact to sensitive habitats; loss of 100 acres of vegetation	Temporary impacts to wildlife during operations due to noise; no impact to sensitive habitats or threatened and endangered species; 1088 of less than 50 acres of previously disturbed vegetation;	No impact
Cultural Resources	No adverse impacts	No adverse impacts to potentially significant historic resources (CTF) if mitigations identified by consultation process are implemented.	No impact
Geology & Soils	26,000 cubic yards of cut, 37,000 cubic yards of fill; new construction required to meet standards for Seismic Zone 4	11,000 cubic yards of excavation. New construction required to meet standards for Seismic Zone 2b.	No impact
Noise	Temporary impacts to wildlife during operations; 390 acres exposed to 60 dBA or greater	Temporary impacts to wildlife during operations; 390 acres exposed to 60 dBA or greater	No impact
Water Resource	No impact on water table or water quality	No impact on water table or water quality	No impact
Health & Safety			
Max. Yearly Release	.16% of natural dose	.34% of natural dose	No impact
Total Lifetime Dose	.07% of natural dose	.14% of natural dose	No impact
Max. Cage Accident	6.1% of natural dose-•	7.5% of natural dose-•	No impact

Figure 4.2-1 Summary of Impacts from Alternatives

The guidance of this document, the specific implementation plans, and the safety assessments provided the bases for convincing demonstrations of safety necessary to gain approvals for development, testing, demonstration, and, ultimately, utilization of the PBR technology for nuclear rocket applications. Specifically, full compliance with the requirements assured that all activities met or exceeded requirements set forth in all local, state, and federal environmental, health and safety regulations and laws.

The document addressed safety policy, implementation guidelines, safety goals and requirements, and safety assessment and documentation. In addition, the potential for significant damage to the testing sites and facilities, or to public or private property, was addressed. The policy dealt with all credible accidents that could occur during ground testing, and accidents involving the reactor systems during launches. For ground tests, the policy covered occupational and environmental hazards, as well as possible reactor accidents. For

launches, occupational and environmental hazards not associated with the engine systems were the responsibility of the controlling launch site organization.

Project teams had environmental, health, and safety responsibility for nuclear and hazardous materials when they arrived at the test site and until transferred to appropriate organizations. The policy did not directly address the safeguarding of hazardous materials or special nuclear material (SNM), but did recognize that there were important interfaces between safety and safeguards operations. All SNM safeguards requirements would meet DOE orders.

The policy document contains the following major elements:

- Statements of the purposes and scope of the document.
- SNTP program safety policy.
- SNTP safety goals.
- Description of the management structure in place to assure safety.
- Description of technical approaches and strategies to assure safety throughout the work in the SNTP program and safety in the SNTP products.

This established safety as an essential and integral part of the SNTP program.

The SNTP program was committed to achieving the highest practicable levels of safety both in program activities and in the ultimate product of the program. Safety considerations included protection of the:

- health and safety of the public.
- health and safety of all employees.
- environment and lands from contamination or damage.
- property and facilities used in the program.

It was the policy of the SNTP Program that:

- Safety and environmental protection would be explicitly considered and incorporated into each activity or system activity.

- Safety considerations would explicitly include consideration of off-normal and accident situations.

- All mandated, statutory, and legal requirements for safety and environmental protection would be met. These include Air Force flight and launch site safety recommendations, DOE Orders, National Environment Policy Act (NEPA) laws and Occupational Safety and Health Act (OSHA) laws. Careful consideration would be given to satisfying principles established by the Scientific Subcommittee and Legal Subcommittee of the United Nations Committee on the Peaceful uses of Outer Space regarding the use of nuclear power systems in space where they apply to nuclear thermal propulsion. Principles set forth by the International Energy Agencies International Nuclear Safety Advisory Group "Basic Safety Principles for Nuclear Power Plants", Safety Series

No.75-INSAG3, would be followed to the degree relevant to this technology and its subsequent applications. Launch of the system for any future demonstration flight would be subject to approval by the Office of the President as described in Presidential Directive No. 25 which includes review by an Interagency Nuclear Safety Review Panel.

- Compliance with these requirements would be based on the principles of defense-in-depth involving multiple physical, procedural, and administrative barriers.

- To the extent practicable, the SNTP Program would seek to achieve the highest levels of safety in the design, testing, operating, demonstration, and utilization of the SNTP technology. Risks to the public, employees, and the environment, whether from normal operations or accidents, would be reduced to levels below those sought by mandatory requirements considering project resources, the state of technology, and the benefits to be accrued from the program. Every practical effort would be made to maintain risks due to radiation and toxic material exposures as low as is reasonably achievable (ALARA).

- Line management would be responsible for compliance with safety policies. Each individual would share in the responsibility to achieve, demonstrate, and document outstanding levels of safety and environmental protection.

The program would include testing fuel elements to failure. There were three major reasons for this safety-related testing:

- To identify and characterize the failure mechanisms
- To quantify the design margins at operational conditions
- To develop a basis for estimating probabilities of failure at operational and accidental conditions.

Testing would be confined to fuel sample and fuel element tests under prototypic conditions to minimize risks. Testing of full-scale systems would be needed only to confirm that sub-scale tests had been adequately representative.

Tests would be conducted only under test conditions which will assure that:

- Releases, if any, are below established limits and are ALARA.
- The probability and consequences of any releases are as low as practicable.

Deliberate testing to failure of a fuel sample is considered neither an accident nor an unusual occurrence. However, it is necessary to assure, with a high degree of confidence, that such failures are not expected to result in hazards higher than the limits imposed for other operational activities.

Safety Goals

The project team would, to the extent practical, attempt to achieve a set of probabilistic safety goals. These goals would facilitate comparison to the risks from other, similar governmental and commercial activities. These goals should be considered targets and not fixed requirements.

The intent of the program team was to use the safety goals to show that:

- For ground testing, the risks to the public and site workers would be less than or comparable to the risks from currently operating commercial reactors and DOE production reactors.
- For launch operations, the risks to the public and site workers would be less than or comparable to the risks associated with current operations involving radioisotope thermoelectric generators (RTGs).
- For all phases of the program, the risks of significant environmental damage would be small.
- For ground testing, the risks of loss of the testing facility or possible contamination of the test site would be small.

Quantitative safety goals were developed for this program based on the currently proposed NRC and DOE safety policies. The two quantitative safety goals for this program are:

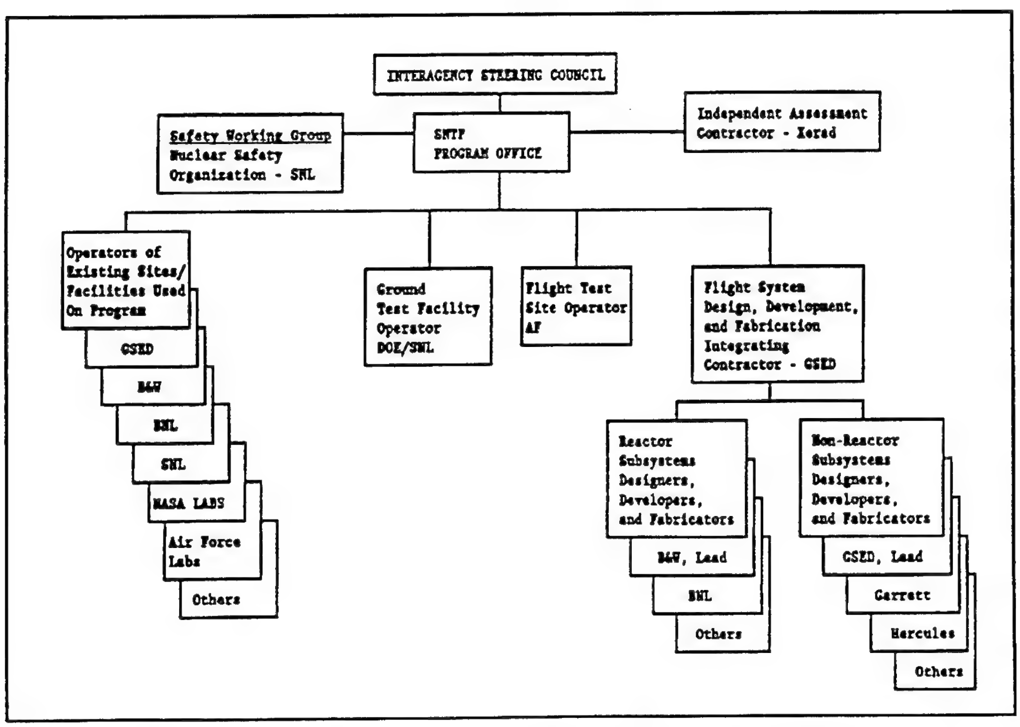


Figure 4.2-2 Line Organization Structure - Safety

1. Health Risks:
   The prompt fatality risk to individuals from radiological exposures resulting from accidents during project operations should not exceed one tenth of one percent (0.1%) of the prompt fatality risks to which the U.S. population is normally exposed.

   The latent cancer fatality risk to individuals from radiological exposures resulting from accidents during project operations should not exceed one tenth of one percent (0.1%) of the latent cancer risks to which the U.S. population is normally exposed.

2. Environmental Protection and Loss of Facility Risks:
   For ground testing, the frequency of accidents involving significant unfiltered radiological releases from the reactor to the site and/or the surrounding environment should not exceed 10^{-4} per calendar year of facility operation.

Management Organizations and Responsibilities for Safety

A fundamental principle of the SNTP Program was that safety is a line management responsibility. Figure 4.2-2 shows the line organization structure pertaining to safety. Specifically, each participating agency or company was fully responsible and accountable to the SNTP Program for meeting all environmental, health and safety requirements for each activity conducted on their sites.

Identification of Flight Safety Issues

ES&H considered the identification of the safety issues related to the flight demonstrations and eventual applications proposed for PBR space propulsion systems. These issues include safety concerns associated with launch, operations (in orbit and on extra-terrestrial trajectories), shutdown, potential reentries, disposal, etc. The activities included:

- Characterization of candidate missions
- Descriptions of applicable propulsion systems
- Identification of hazards
- Identification of applicable regulations and guidance
- Safety assessments, including the development of tools and data, estimates of safety/environmental impacts, and the definition of safety design requirements
- Documentation and presentation of results

Preliminary results were to be available by about July, 1993.

4.3 WBS 1.3 Mission Applications

4.3.1 Overview

The fundamental reason for development of any new technology is to significantly improve upon existing capabilities or provide a capability that did not exist before. Ideally, the new capability would satisfy a definite user need. As in the case of essentially all previous nuclear programs, gaining sustained and strong user support for the SNTP program proved to be difficult. Nevertheless, the mission applications work established a multitude of potential space missions that would significantly benefit, and in some cases be enabled by the significant performance improvement offered by the SNTP system. For each of the candidate missions identified, realistic mission scenarios were identified and used to synthesize practical overall system design and performance requirements, which in turn were used in engine system studies to define engine requirements, features and characteristics.

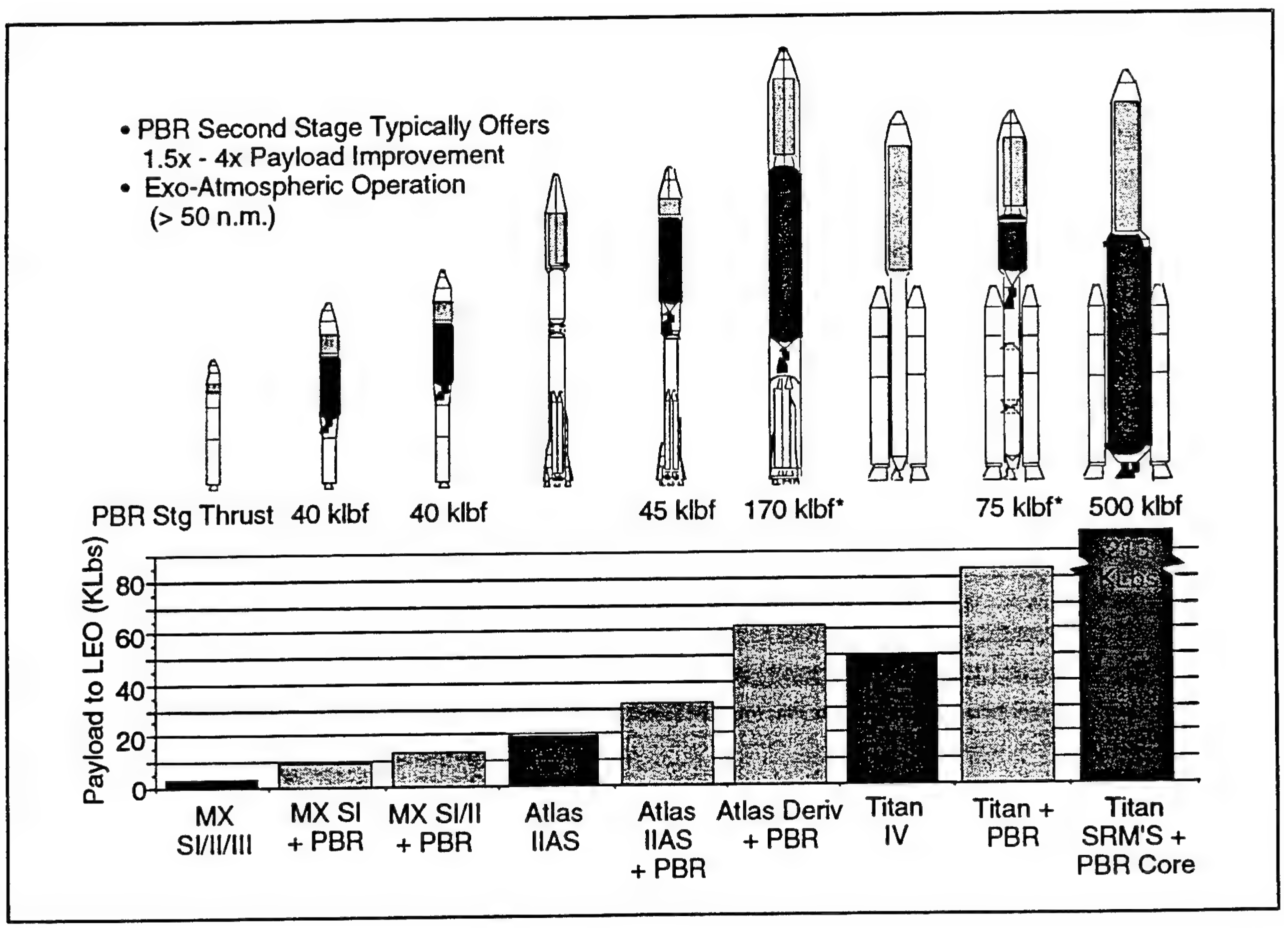


Figure 4.3-1 Typical Upper Stage Applications

4.3.2 History

The performance advantage that the SNTP system would have over chemical propulsion could enable dramatic performance benefits in an extremely broad range of mission categories. Mission analysis efforts broadened in scope significantly from the Phase I SDI interceptor mission in the late 1980's. Focus shifted to launch vehicle upper stages and orbit transfer vehicles early in Phase II in the 1990-1991 time frame. Investigations into bi-modal applications were initiated in the summer of 1992, and the focus of mission analysis efforts gradually shifted away from purely propulsive missions to more flexible bi-modal propulsion/ power missions that could be more useful to the Air Force.

Analyses conducted in Phase I demonstrated the usefulness of the technology for the interceptor mission in various forms. A ground-based ICBM/SLBM interceptor with a Peacekeeper first stage and an SNTP second stage could accomplish several roles in a mass-raid scenario, as well as permitting deployment of a treaty-compliant limited protection system. In the latter role, the SNTP-equipped interceptor would be capable of defeating enemy missiles before they overfly the continental United States, from a treaty-compliant single site in North Dakota.

Mission analysis efforts also focused on various mission-related aspects of engine system design. Radiation shielding, cooldown propellant, and safety studies were performed by or with the support of the mission analysis team. Several performance-building strategies were developed that contributed significantly to the advantages the SNTP system holds over chemical and competing nuclear systems.

4.3.3 Missions

The range of missions analyzed during the course of the SNTP program can be grouped into two broad categories, based on whether first ignition of the SNTP engine occurs sub-orbitally or after a stable orbit has been achieved. Below is a review of missions analyzed with brief synopsis of results.

Second Stages (Sub-Orbital Start)

SNTP provides dramatic payload improvements when used as a high-energy top stage for Earth-to-Orbit launch systems. In these applications, operation of the SNTP was limited to the Exo-Atmosphere, with ignition occurring at altitudes > 50 nmi. Even with Exo-Atmospheric operation, significant safety issues, both real and perceived, were raised, making user agencies negative toward this application. "Advanced Top Stage" (ATS) configurations were developed (to varying degrees) for the following boosters/launch systems:

- Atlas IIAS
- Titan III, IV
- Advanced/National Launch System
- Spacelifter
- Peacekeeper
- Minuteman
- Delta

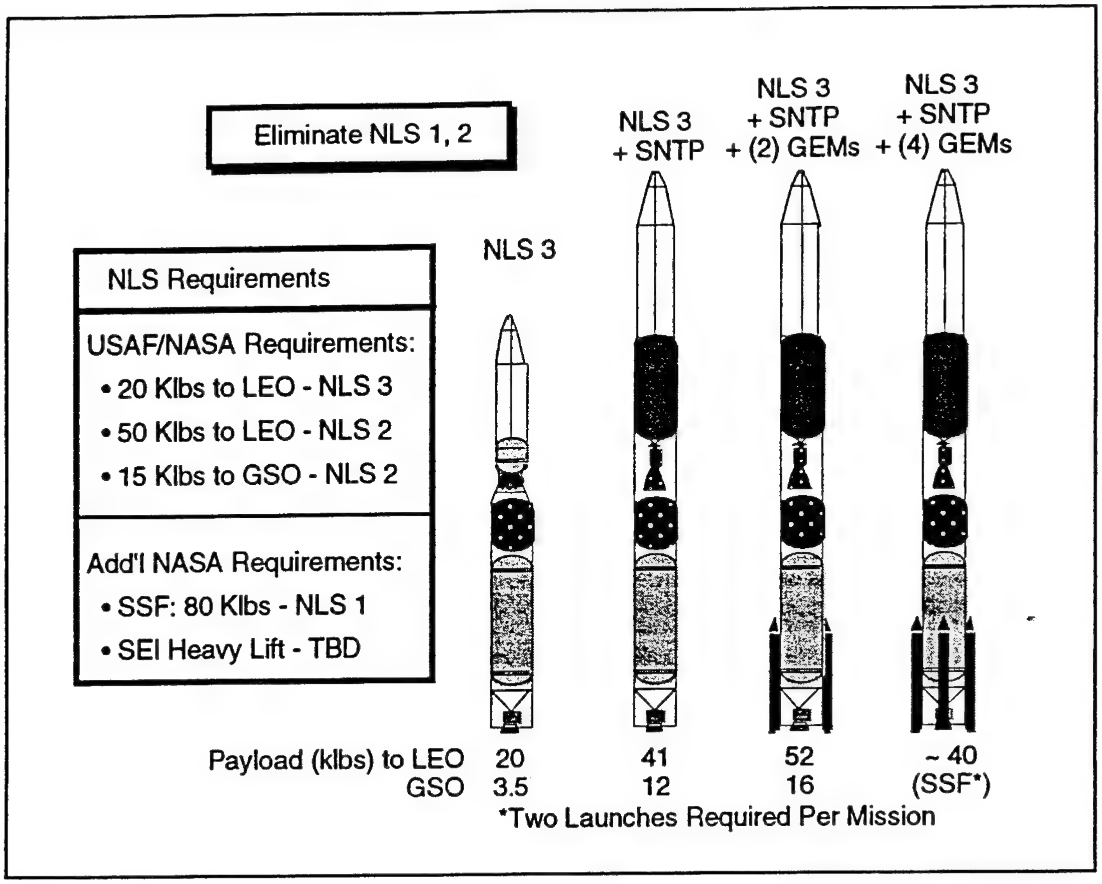


Figure 4.3-2 SNTP Applied to National Launch System

Payload improvements to Low Earth Orbit vary from 1.5x to 4x that of the conventional systems, depending on which system is being modified and how much alteration of the basic system is acceptable. Figure 4.3-1 depicts representative LEO payload capabilities for a range of vehicle options, as well as for several chemical-only systems.

Large increases in payload generally require greater changes, additions, or modifications to the booster vehicle. The need for these modifications stemmed from such factors as the very low density of LH_2 (resulting in large tanks) and the fact that increased payload/ATS mass decreased vehicle thrust-to-weight at ignition (T/W_{ign}) to an unacceptable level. If T/W_{ign} drops below 1.15, booster controllability becomes an issue, and the vehicle has trouble getting off the ground.

Since it was found during the course of the SNTP program that there was little user interest in increasing payload capability beyond the largest currently available system (Titan IV/Centaur) for USAF missions, the greatest benefit of SNTP for the ETO mission derived from potential cost savings enabled by matching the Titan IV capability with a smaller/cheaper booster such as Atlas or Spacelifter. Although Titan/Centaur performance to GSO could be tripled with ATS replacing Centaur, little market was perceived for a >30 klb satellite in GSO. Instead, studies were conducted to determine how an Atlas first stage could be used in conjunction with an ATS to match/exceed Titan IV/Centaur performance.

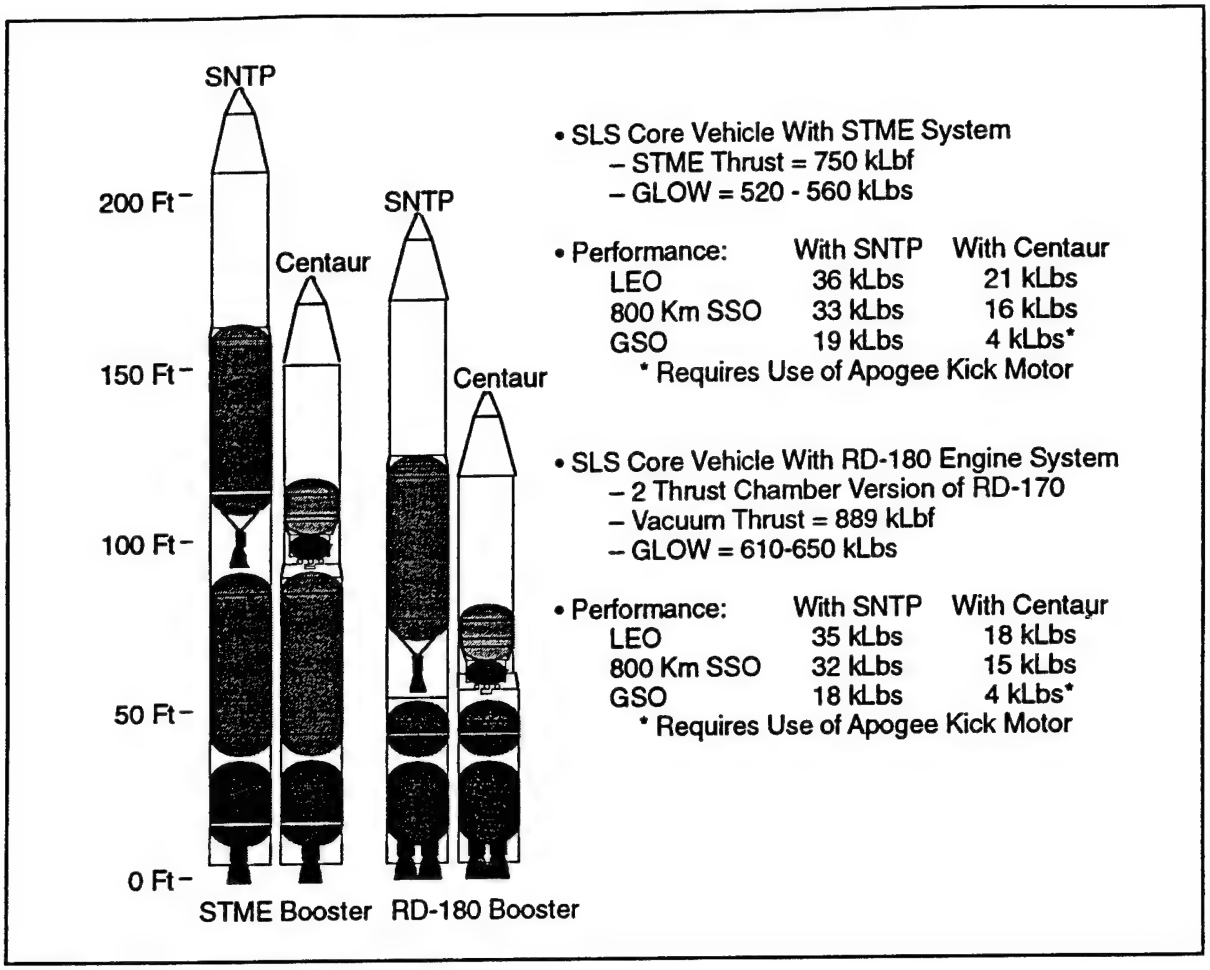


Figure 4.3-3 Spacelifter Systems With SNTP and Centaur Top Stages

The Atlas/ATS vehicle was the subject of extensive analyses and design iterations. In the end, two vehicle options were presented. The first utilized a "stock" Atlas IIE first stage (Atlas IIAS with enhanced SRM's replacing the Castor IVA strap-ons) with a size and thrust optimized ATS. Performance to GSO was improved by about 50%, utilizing a single SNTP engine at 62 klbf. While this configuration achieved dramatic performance improvements, and could capture a portion of the Titan market, it fell short of providing an alternative to Titan IV/Centaur.

This approach was hindered by two aspects of the launcher; thrust at ignition and stage diameter. Although the ATS was sized at a diameter of 16.7 feet (whereas Atlas has a diameter of 10 feet), stack height was still a problem, and the Atlas/ATS configuration was somewhat unwieldy. These problems were addressed by a reconfiguration of the Atlas stage. The 4 SRM's, originally ignited in pairs, were all ignited at liftoff to increase T/Wign, and the stage tankage was reconfigured to a 16.7 ft diameter. These changes enabled use of a larger ATS with triple the propellant load of the ATS in the first configuration. The larger size mandated the use of two SNTP engines at 80 klbf, and resulted in payload performance exceeding that of Titan IV/Centaur to all orbits (LEO, GTO, GSO).

ETO analyses were also performed with the Advanced/National Launch System in its various forms. The chief advantage of using an ATS on this booster stems from the fact that it is a "paper" design, and therefore alterations to accommodate SNTP interfaces are far more easily accomplished and attractive to users. Explorations of mission options for NLS were conducted in detail during the Space Launch Integration Study effort for the Air Force, and concluded that SNTP can be incorporated into the NLS architecture in such a way that the need for the large (27.5 ft diameter) NLS vehicle is eliminated. The original NLS architecture used a "small" 18 ft diameter booster for launches in the 20 klb class, and a "large" 27.5 ft diameter booster for heavier launches. SNTP and minor reconfiguration of the 18 ft booster resulted in a NLS/ATS vehicle that accomplished the missions originally planned for the large NLS vehicle. This resulted in an estimated life cycle cost reduction of $4 billion. Details of the NLS study may be found in the Space Launch Integration Study final report, and a summary of the "best" architecture is depicted in Figure 4.3-2.

SNTP was also studied relative to "Spacelifter" in various forms. Since less definition for Spacelifter pre-existed the study, more options were considered. Spacelifter/ATS exercises were performed at a first-order level to validate the concept, and excellent results were obtained. Spacelifter configurations were developed with STME and Russian RD-180 engine systems, and performance to GSO of 18-19 klbs was achieved with attractive, compact configurations. An architecture consisting of a single Spacelifter booster equipped with a single RD-180 or thrust-optimized STME and either a Centaur or ATS top stage performs the full Air Force mission architecture with ample performance margin. SNTP engine thrust level for the Spacelifter study was set to 41 klbf, significantly smaller than that used for Atlas. This is a result of better first stage performance due to the greater thrust of the Spacelifter engine, whether it be STME (up-scaled to 750 klbf) or RD-180 (889 klbf). Spacelifter systems are depicted in Figure 4.3-3.

Exploration of performance improvements on the smaller launchers (Delta, Minuteman, Peacekeeper) indicated little real benefit by adding SNTP. Doubling payload performance of a Delta puts it into the Atlas class. Since an Atlas launch is not much more expensive than a Delta launch, it seems unlikely that any effort at developing a Delta top stage would be cost-effective from a payload mass standpoint. However, if a low cost, small SNTP upper stage could be developed, the use of Peacekeeper and Minuteman missiles being taken out of service could have proven cost-effective.

SNTP's clearest benefit for sub-orbital start ETO missions appeared to center around "step-down" applications. The ability to launch Titan or Shuttle-class payloads on a smaller, cheaper launcher held significant promise, both from the standpoint of reducing launcher costs and from the standpoint of eliminating a separate set of facilities for large launchers.

Orbital Transfer/Maneuvering Vehicles (On-Orbit Start)

Orbital Transfer Vehicle (OTV) applications were studied to broaden the utility of the SNTP and to provide an alternative to sub-orbital start second stages. From a safety perspective, OTV's avoid the controversy and complications of sub-orbital start by starting from a "nuclear-safe" orbit. OTV's would typically be used to raise a payload from a low parking orbit to geosynchronous orbit. They would either replace or operate in conjunction

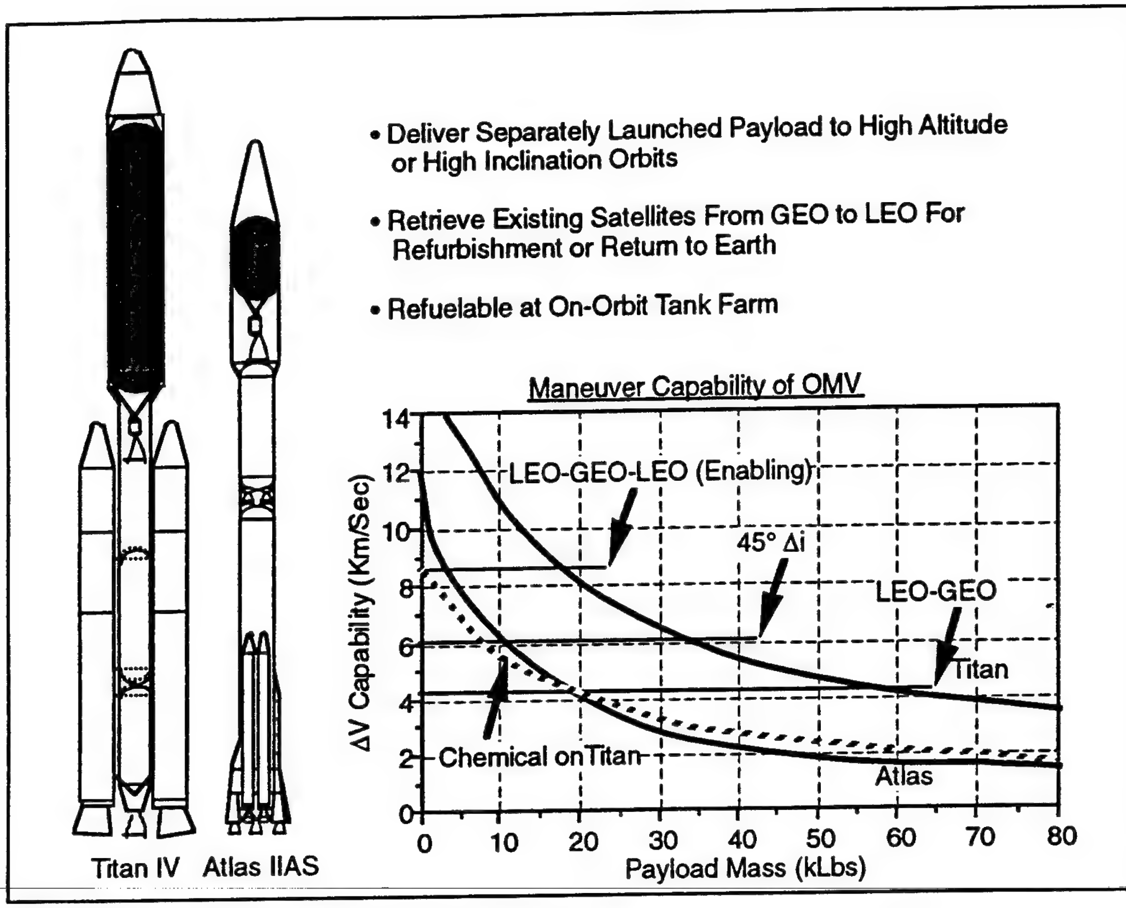


Figure 4.3-4 Orbital Maneuvering Vehicles

with existing second stages on launchers, depending on whether the launcher needs the second stage to reach LEO.

As defined during the SNTP program, OTV's are launched with payloads attached, and Orbital Maneuvering Vehicles (OMV's) are launched separately, and rendezvous with payloads in orbit. OTV and OMV missions require SNTP systems with thrust levels in the 10-30 klbf range, and benefit substantially from high thrust-to-weight. Smaller engines translate directly into larger payloads, and are required to make the missions effective with smaller (Atlas-class) launchers.

Atop an Atlas-class launch vehicle, an SNTP-equipped OTV could improve payload performance to GSO from the typical 3-4 klbs to 7-8 klbs. While this would not accomplish step-down from Titan IV/Centaur, which can deliver 10 klbs, it would provide dramatic payload improvements, and could permit the Air Force to plan future payloads without relying on the Titan IV while maintaining satellite capability. OTV's on a Titan III readily accomplished the step-down from Titan IV, delivering up to 14 klbs to GSO vs. 10 klbs for the Titan IV/Centaur.

In lieu of payload improvements, SNTP performance benefits could be applied to retrieval of the OTV stage back to LEO or capture/return of another satellite from GSO to LEO. SNTP could enable a "round-trip" delivery of approximately the same payload as the "one-

way" chemical mission e.g. 3-4 klbs on an Atlas-class launcher, and 10-11 klbs on a Titan IV-class launcher. Return of the stage alone to LEO for reuse raises payload to GSO capability to a level between the "full round trip" and the one-way missions.

OMV's could be used in the same mode as OTV's, i.e. for GSO-oriented one-way and round-trip missions. OMV's demonstrated greater payload efficiency than OTV's, since separate launch of payload and transfer stage resulted in larger, more mass-efficient transfer stages in orbit. More interestingly, OMV's could be used to accomplish major repositionings of payloads already in orbit. An OMV launched on a Titan IV would be capable of changing the orbital inclination of a KH-11 class surveillance satellite (>30 klbs) in low orbit by 45°. Smaller payloads could be moved even more drastically. Representative OMV configurations and performance are depicted in Figure 4.3-4.

4.3.4 SNTP-Related Issues

Although there are many areas to be addressed in developing a new propulsion stage, certain key issues are unique to nuclear propulsion and bear special attention. Four areas of mission/vehicle design were addressed in detail during the SNTP program. These are:

- Safety concerns, including inadvertent re-entry and nuclear-safe orbits
- Management of reactor decay heat
- Nuclear heating of the propellant
- Low density of hydrogen propellant.

Mission Safety

Safety analyses centered on concerns over avoiding the potential for contamination of the Earth's biosphere from radioactive fission products present in the SNTP reactor after operation has commenced. Safety in this regard was addressed in three separate areas: prevention of inadvertent reactor start-up prior to initial start, analysis of the consequences of a failure during SNTP operation in a sub-orbital start mission, and analysis of the requirements centering around a Nuclear-Safe Orbit (NSO) mission groundrule.

Inadvertent start-up and post-startup failure consequences were addressed in some detail in the Space Launch Integration Study. The conclusions of that assessment included the following points:

- Inadvertent start-up can be precluded in all foreseeable accident scenarios by the triple-redundant safing system incorporated into the reactor design (Section 4.4.3).

- The possibility of failure after startup, but prior to achievement of a stable orbit is best addressed by designing the reactor such that it disintegrates and disperses over a broad area. Upper atmosphere vaporization leads to radiation hazards below background levels. Particulate dispersal over a "footprint" leads to a worst-case exposure level approximately equal to one dental X-ray. Intact re-entry and recovery was subject to a first-order assessment. It was concluded that the threat can be mitigated by incorporating a shield around the reactor into the engine design, but that there is a significant performance penalty associated with this approach.

On-orbit start mission studies conducted by members of the nuclear propulsion community often avoid concerns about inadvertent re-entry of radioactive reactors by assuming that initial operation takes place after achievement of a Nuclear-Safe (or Sufficiently High) orbit. The initial mass penalty of using such a mission groundrule made a detailed study prudent. Conventional approaches involved using an orbit (typically 800 km circular) with an initial life of hundreds of years. Since the SNTP reactor poses no radiation hazard before initial operation, the conventional approach was deemed excessive. Analysis demonstrated that an initial parking orbit of 148 x 800 km coupled with initial SNTP operation at apogee would satisfy safety criteria, and would reduce the payload penalty of the "conventional" approach by 50%.

Management of Reactor Decay Heat

The fission products generated during operation of the SNTP system decay at a rate sufficient to produce unacceptable heating within the reactor after shut-down. The approach taken to address this problem involves open-loop cooling of the reactor after shut-down with additional propellant carried in the stage expressly for this purpose.

A decay heat propellant estimating algorithm was generated from ANSI decay data and some assumptions, and was later validated by comparison to other predictors. Typically, decay heat required an additional propellant load of 3% to 8% of the propellant consumed during normal operation. This fraction varied with engine operating time, and decreased as run time increased. This is due to the fact that short-life fission products created early in the burn generate their decay heat during the latter portion of the burn, before shut-down. This phenomenon can be utilized to reduce decay heat propellant penalties by throttling the engine down to approximately 20% power for the last portion of the burn. This throttling must be balanced against mission needs, resultant gravity losses, and engine system requirements and constraints, but it could be effectively implemented in some mission scenarios.

Propellant Nuclear Heating

Radiation (neutrons) leaking from the reactor during full-power operation and impinging on the bottom of the propellant tank generates substantial localized heating in the hydrogen. Analyses have shown that this heating rate is sufficient to boil the liquid hydrogen in the bottom of the tank, resulting in lost propellant, requirements for a more robust venting system, and the potential for two-phase flow through the pump(s). Radiation impingement on the tank was mitigated by including a radiation shield within the engine pressure vessel (between the core and the engine upper dome). Although shielding requirements can vary substantially with vehicle configuration and engine power output, a representative configuration reduced radiation impinging on the tank by a factor of 3. This was sufficient to eliminate the possibility of propellant boil-off during operation.

Shielding mass is a direct penalty on payload performance, i.e. one pound of engine shielding translates to one pound of payload for most missions. One option for reducing shield mass is lengthening the engine thrust structure to increase the physical separation between the engine and the tank. This must be balanced against additional thrust structure weight,

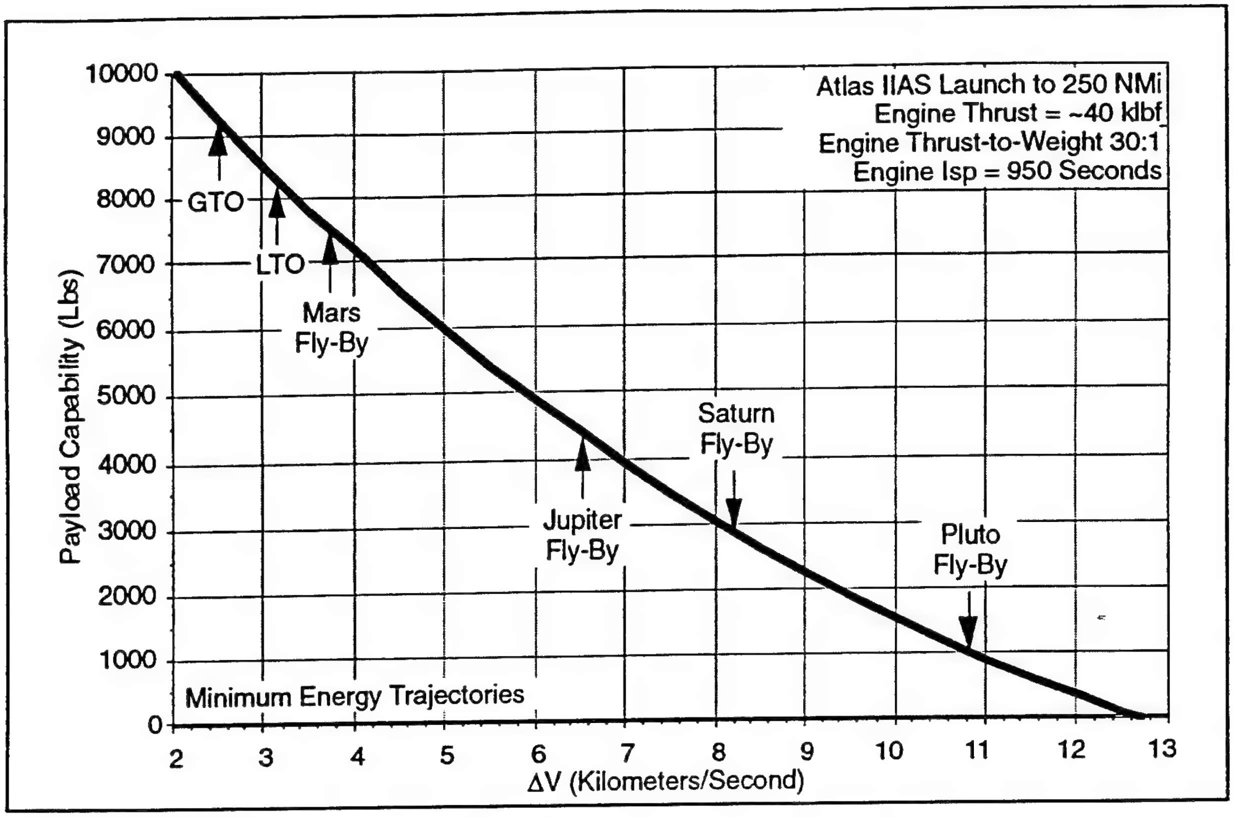


Figure 4.3-5 Candidate Flight Test Missions

additional interstage weight, and lost payload volume. This approach is very mission-specific, and cannot be implemented effectively until a well-defined mission (or mission set) is first established.

Low Propellant Density

The SNTP system's use of LH_2 as the only propellant introduces a major design complication into vehicle configuration studies. Since LH_2 has an extremely low density in comparison to other propellants/propellant combinations, nuclear stages tend to be much larger than the norm. This creates problems in both second-stage and on-orbit applications. In second-stage applications, replacing the existing stage with an SNTP stage generally leads to large increases in stack height. This creates problems in accommodating the stack with existing gantries and facilities, introduces controllability questions, and places additional structural stress on the boosters. The length problem can be mitigated fairly effectively by increasing stage diameter, but this introduces its own problems. The issue was dealt with by increasing stage diameter substantially, and accepting some increase in length.

Tank volume requirements for on-orbit applications are such that existing launch vehicle fairings cannot effectively accommodate the stage, or can do so only at substantial penalty to the available payload volume. Options for mitigating this problem are development of larger payload fairings, or, more attractively, launching the stage partially unencapsulated. This has implications in stage design, since an unencapsulated tank will experience different structural and heat loads. The Atlas-launched OMV in Figure 4.3-4 illustrates this partially-

unencapsulated approach, and was necessary because the large Atlas fairing is too short to accommodate SNTP. One other volume-saving technique involves launching the vehicle in an "engine-up" configuration, allowing the relatively small diameter of the engine to reach well into the nose cone, and eliminating the wasted space that would result from launching the stage "engine-down."

Another candidate approach for reducing tank size in volume-critical applications was the use of slush H_2, which is approximately 15% more dense than liquid H_2. Handling and flow issues were not addressed.

4.3.5 Flight Test

Although flight test was outside the scope of the SNTP Phase II program effort, a first-order assessment of "piggy-back" payloads and missions was made to determine whether an SNTP flight test could be exploited by some user with a payload. It was assumed that a first flight test would begin in a stable Earth orbit, and perform a single burn. Launch atop an Atlas IIAS or equivalent booster was also assumed for the purposes of determining initial vehicle mass. The parametric chart of payload vs. generated velocity, depicted in Figure 4.3-5, shows the potential flight test vehicle performance to various targets.

"Piggy-backing" a useful payload on a flight test could help defray the costs of an SNTP flight test program, and was used in program advocacy efforts.

Below are listed a number of reports and memoranda that discuss in detail the missions and issues summarized in this section:

SNTP-M-GRU-91-30 dated 19 March 1991, "Atlas Upper Stage Engine Shielding Requirements."

Space Launch Integration Study Technical Report - Study-Services dated 15 June 1992. Contract No. F04701-91-C-0112, CDRL A004

SNTP-M-GRU-92-225 dated 8 October 1992, "Earth-to-Orbit Launch Vehicles with RD-170 Engine."

SNTP-M-GRU-92-230 dated 12 October 1992, "RLS Vehicle Options Fulfilling USAF & NASA Requirements."

SNTP-M-GRU-92-249 dated 2 November 1992, "Proposed Strawman Engine Parameters to be Used for Mission Analyses."

SNTP-M-GRU-92-306 dated 1 December 1992, "Proposed Groundrules and Criteria for DRM Selection."

SNTP-R-GRU-92-011 dated 4 December 1992, "Identification of SNTP Design Reference Missions."

SNTP-M-GRU-93-012 dated 22 January 1993, "Prediction of Propellant Required for Decay Heat Removal."

SNTP-R-GRU-93-006 dated 29 April 1993, "Preliminary Mission-Derived Engine Requirements: DRM 1 - Earth-to-Orbit Second Stage."

4.3.6 Conclusions

The SNTP mission analysis effort demonstrated the broad utility of an SNTP system. Substantial improvements in vehicle performance were defined, permitting accomplishment of new missions and more efficient performance of existing missions. Smaller launch vehicles enabled by SNTP promised dramatic reductions in launch costs and launch system complexity. Greater propulsive efficiency offered to in-orbit propulsion systems would permit larger payloads and new mission classes, improving military access to space.

The mission analysis effort identified and quantified many of the issues unique to integration of a nuclear propulsion system into a space vehicle. It was found that these issues did not alter the conclusion that SNTP would be a practical, useful, and highly desirable element of a future space transportation architecture.

4.4 WBS 1.4 Engine System Design and Development

4.4.1 Overview

The Engine System Design & Development (ESD&D) activities established the practical link between the particle bed reactor and an integrated, useful space nuclear thermal propulsion system. ESD&D included extensive conceptual studies and trades and more detailed design and analysis efforts to identify and characterize rocket engine and component element design features and performance that would satisfy a wide range of missions and ground test demonstration requirements. The development of selected critical engine system subsystems, subassemblies and components needed to achieve the high performance specified for a flight engine was also a major part of this effort. The high performance requirements baselined for the flight engine system would have required advancements in the state-of-the-art in the nuclear and non-nuclear component technologies. However, an engine system cycle trade study that was in process when the program ended, might well have established less aggressive technology needs for many of the engine components.

4.4.2 Engine System

Phase II of the SNTP Program started with the LV01 Engine (LV was an internal program designation for the flight engine series) as the baseline. This engine was a high performance, minimum weight configuration that could meet the requirements of an interceptor mission specified by the then Strategic Defense Initiative Office (SDIO). Early in Phase II it was recognized that the LV01 design was limited in its mission utility, and the engine design requirements were revised to include greater thrust (and reactor power), higher Isp and longer burn time (LV02). Finally during this evolution of design requirements, the SDIO baselined the second stage mission for the engine design, and the LV03 designwas initiated.

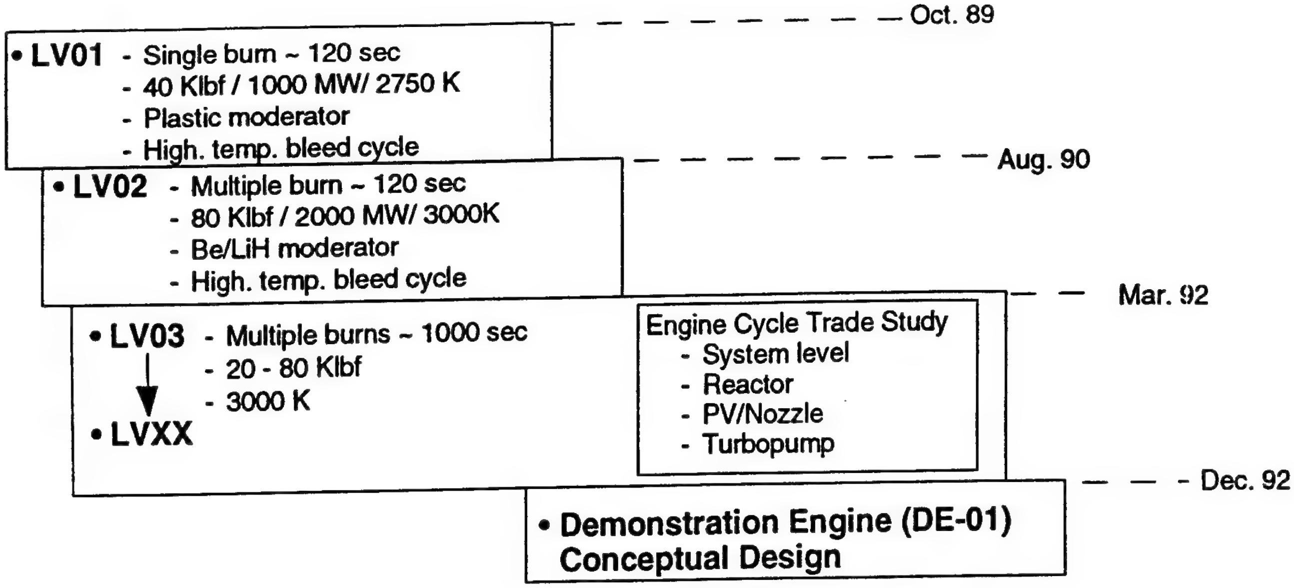


Figure 4.4-1 SNTP Engine System Design Evolution

The engine system design evolution, and the top level system requirements for LV01, LV02 and LV03 are shown in Figure 4.4-1. The most significant changes were the increased engine firing time and the number of restarts.

The Phase I and early Phase II mission requirements placed a large emphasis on light weight (high thrust to weight, T/W) and rapid start capability, in addition to high Isp. Consequently the engine cycle that was baselined for LV01 and LV02 engines was the bleed cycle. In addition, the bleed cycle simplified the reactor design and permitted independent development of the reactor and the balance of the system. This was a significant benefit since the geometry and structural characteristics of the high power density PBR makes extraction of the energy to drive the turbine in an expander cycle difficult. In order to improve the performance of the bleed cycle, a high temperature turbine design (2D polar weave carbon-carbon) was selected for LV02 The bleed cycle was carried over to the LV03 design, and was shown to meet all the design requirements.

Later in Phase II, after the AF became the program sponsor, they requested that the SNTP be capable of performing several missions including the second stage, deep space and earth orbital applications. Design reference mission (DRM) requirements were derived, and the necessary technology levels were being evaluated as part of an engine cycle trade study. The AF revised program priorities placed heavy weight on reducing program risk, and maintaining traceability between the Demonstration Engine and the final flight engine version.

The Phase II engine design development effort was last focused on LV03, and those accomplishments will be discussed herein. The results of the cycle trade study in progress will be discussed at the end of this section.

Performance and Design Requirements

The derivation of performance and design requirements was a combination of technology push and mission utility pull. Since there was no specific mission from which firm requirements could be derived and flowed down, the approach was to set high goals and remain flexible to user needs and technology developments. The goals were set as high as possible to obtain the most beneficial utility for the SNTP PBR Engine. Impact of pursuing these performance goals on program cost and schedule were continuously monitored and assessed, and the goals changed accordingly. These assessments usually corresponded to the funding cycle when SNTP management priorities were established for the coming fiscal year. The latest set of requirements for the LV03 design that the SNTP Project Team was working to are shown in Figure 4.4-2. As can be seen from the figure, the goal was to have an engine that would be scaleable in the range of 20 klb_f to 80 klb_f of thrust (corresponding to nominally 500 MW_t to 2000 MW_t), with an I_{sp} of 930 sec and an aggressive thrust/weight (T/W) ratio of at least 25. These performance goals were arrived at by assessments made of the limitations on thermal hydraulics (power density), carbon-carbon material properties and fuel performance being developed for the Program,. To develop the LV03 design, a thrust level of 40 klb_f was selected with reactor power of 1000 MW_t. The remainder of the design requirements (number and duration of engine burns, start transient and throttling requirements, etc.) were derived from analyses of upper stage, GEO,GTO and orbital missions.

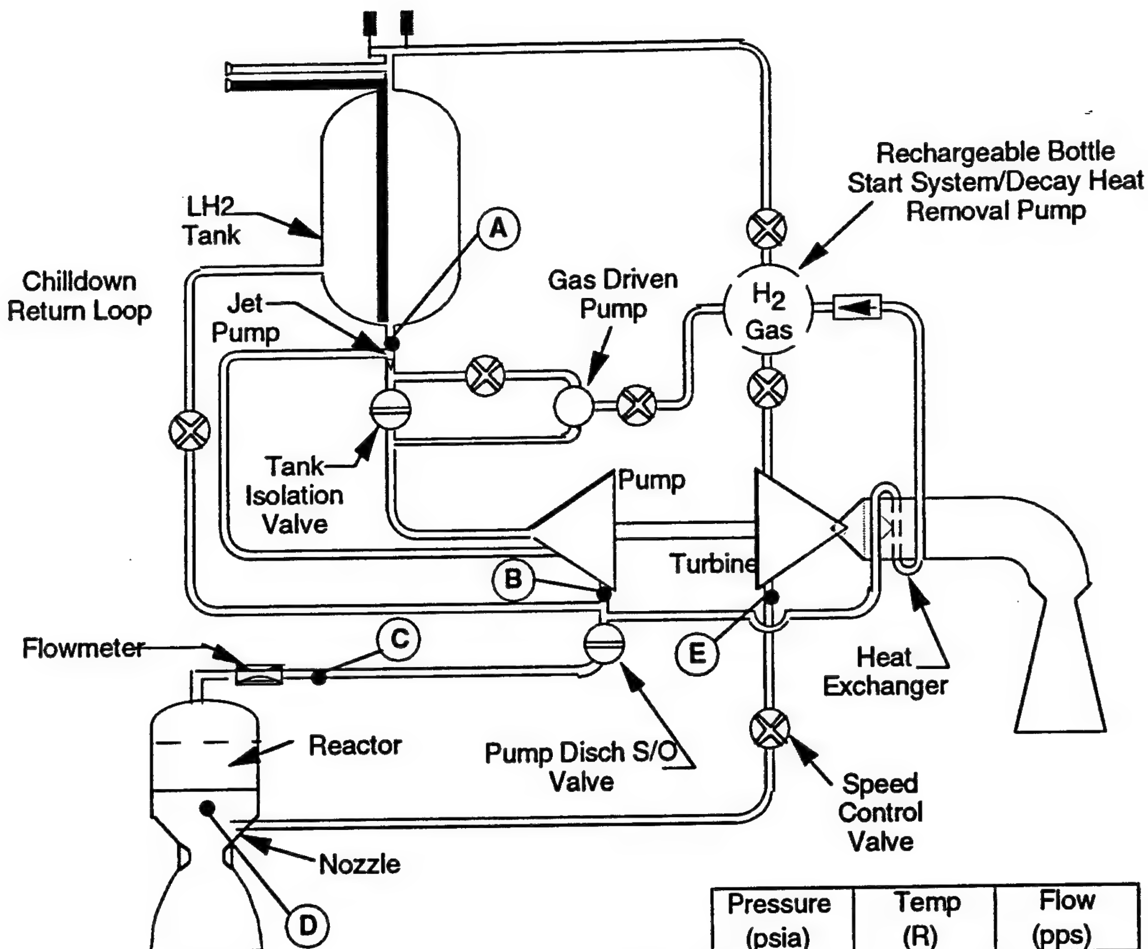
	Performance	Design
Engine Thrust	20 - 80 Klbf	
Engine Power	500 - 2000 MW	
Specific Impulse at Full Thrust	930 sec.	
Engine Chamber Temperature		3000 K
Turbine Inlet Temperature		2750 K
Engine Chamber Pressure		1000 psia
Engine Thrust-to-Weight Ratio	25 - 35:1	
Nozzle Expansion Ratio		100:1
Maximum Throttling Ratio		5:1
Number of starts		3
Start Transient: 0 -100%		10 sec.
Engine Firing Time:		
Full Power		600 sec.
Full Power + 20% Power		500+700 sec.
Maximum Coast Between Burns		5.5 hrs.
Minimum Coast Between Burns		600 sec.
Chamber Temp. during Coast		1100 - 1500 K

Figure 4.4-2 SNTP Engine Performance and Design Requirements

Cycle Description

As discussed earlier, the hot bleed cycle was selected for the engine. The selection was initially based on the lower mass and more rapid startup capabilities of the bleed cycle compared to the expander cycle. Although changing mission requirements reduced the need for minimizing system mass, the bleed cycle was retained because it would have decoupled the reactor development from the balance of plant (BOP). This could have reduced the development risk of the reactor, but would have required development of high technology carbon-carbon turbine and bleed system.

Figure 4.4-3 shows the SNTP engine system bleed cycle schematic. The feed system routes low pressure propellant (liquid hydrogen) to the turbopump, which raises the propellant pressure level and forces it through the flowmeter, neutronic shield, pressure vessel, and



	Pressure (psia)	Temp (R)	Flow (pps)
A	50	43	44.5
B	1350	60	44.5
C	1250	60	43.5
D	1000	5400	43.5
E	850	4950	1.4

Figure 4.4-3 Bleed Cycle Schematic

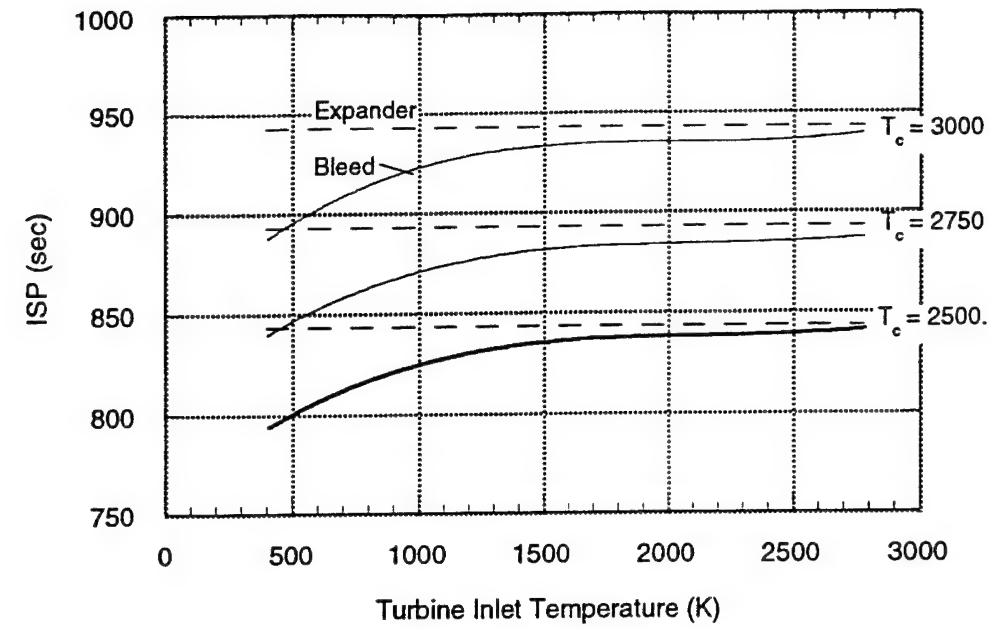


Figure 4.4-4 SNTP Engine System Performance, Bleed & Expander Cycle

into the reactor assembly (moderator, reflector, cold frit, fuel bed, and hot frit), where the propellant is heated as it flows across the nuclear fuel particle bed. The gaseous flow is then collected in the hot frits, flows into the nozzle chamber plenum, and is then ejected through a nozzle at high velocity to produce thrust. With the bleed cycle, the energy required to drive the propellant pump is bled from the thrust chamber and routed into the turbopump power section.

The bleed cycle performance, measured as I_{sp}, is lower than that of the expander cycle. In contrast to the bleed cycle, all the propellant is heated and expanded through the main propulsive nozzle. To improve bleed cycle performance, the turbine inlet temperature is raised to the maximum that can be obtained. This is limited by the materials structural and corrosion/erosion characteristics in the hot hydrogen environment. A comparison of bleed and expander cycle performance is shown in Figure 4.4-4. Also shown in the figure is the effect of turbine inlet temperature. At low turbine temperature the expander cycle is significantly higher in performance, but the difference is only 5-6 sec at the selected turbine inlet temperature of 2750 K. This temperature was estimated from analysis to be within the structural limit for the selected turbine carbon-carbon material technology. It should also be noted that for a given chamber temperature (T_c), a reduction of a few hundred degrees in turbine temperature has a small effect on performance, thus providing a viable risk mitigation approach should turbine development problems arise and jeopardize programmatic objectives.

Engine Characteristics and Mass Properties

An engine isometric and cross-section are shown in Figures 4.4-5 and 4.4-6, respectively. Figure 4.4-5 defines the engine subsystems and the organizations that had primary responsibility for their development. Figure 4.4-6 shows the overall dimensions and the materials of the major components. Design development and material selection of the components will be addressed in their individual subsections.

The engine mass breakdown is shown in Figure 4.4-7. The total mass of the engine was estimated to be 910 kg, not including internal shielding. This yielded a T/W of 21:1, which did not meet the goal of attaining at least 25:1. However, the latest mission studies had shown that this thrust to weight ratio was sufficient to meet and/or exceed all mission utility requirements, and it was therefore accepted in lieu of striving for more performance with potentially more development risk.

Engine Cycle Trade Studies

As discussed earlier, the Program Office expanded the mission utility of the SNTP engine and requested a review of the technologies that would satisfy the broader range of requirements. This initiated an engine cycle trade study that would determine the technology path to a high performing flight engine, with traceability to a (ground) Demonstration Engine that could possibly have less advanced technology with reduced development risk.

The trade study included a wide range of engine cycles, component configurations and materials of construction as shown in Figure 4.4-8. A matrix of over 100 combinations was narrowed down to three cases on the basis of weight, performance or feasibility/complexity of the system.

The cycle schematic flow diagrams of the three cases are shown in Figures 4.4-3, 4.4-9 and 4.4-10, for the bleed, full flow expander and partial flow expander cycles. The bleed cycle, which was discussed earlier, could be most readily integrated into the SNTP engine. The reactor design would not require basic changes, and design and development of the reactor would be essentially independent of the rest of the engine system. However in order to meet the performance goals a high temperature turbine was required. The turbine technology that would be necessary at the specified temperature and hydrogen environment did not exist, and would have to be developed along with the hot portion of the turbine feed system. The LV03 design was used as the bleed cycle case for the trade study.

The full flow expander cycle required that the reactor and propellant management system (PMS) be integrated. Flow is introduced into the reactor to extract heat from the core components (moderator, reflector, structure, shield, etc.) is then fed into a full flow turbine and is reintroduced into the reactor where it cools the fuel bed and is heated up to the mixed mean outlet temperature. The partial flow expander cycle is similar, except that only a portion of the flow is heated in non-fuel components and fed into the turbine. In both of these cycles low temperature turbines and feed systems could be used, for which a substantial data base exists. The challenge here was to extract the required energy from the compact reactor core, and maintain a high thrust to weight. Programmatically, the coupling of the design and development of the reactor with that of the turbine and feed system could pose a risk.

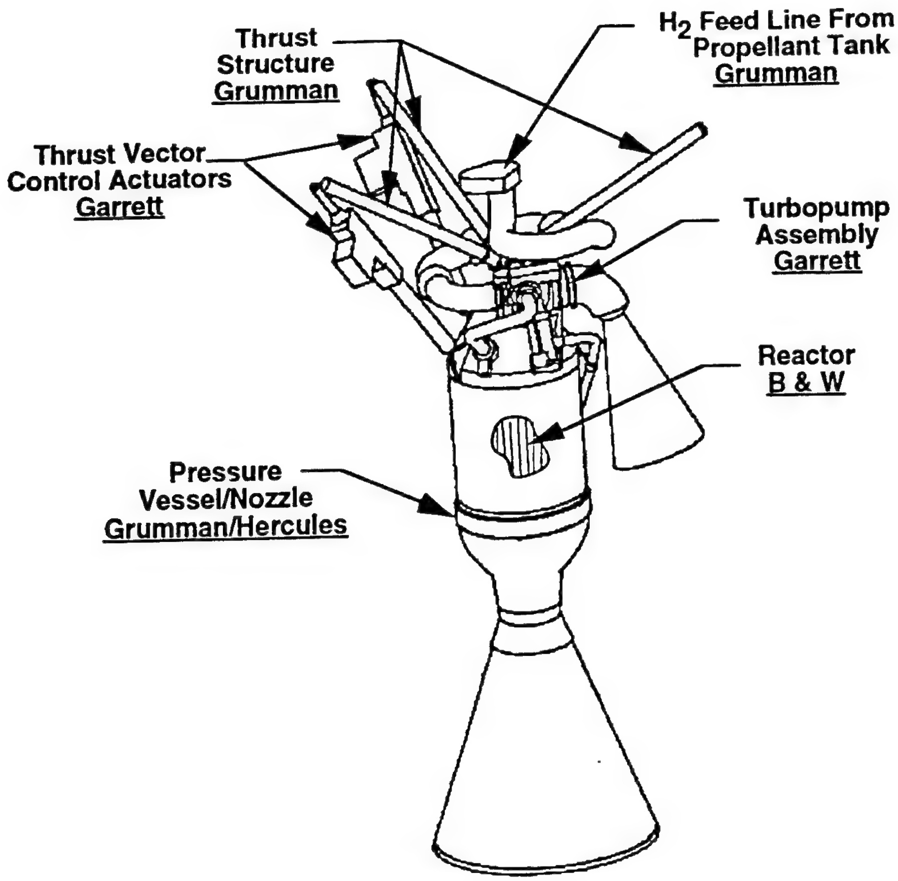


Figure 4.4-5 Engine Isometric Sketch

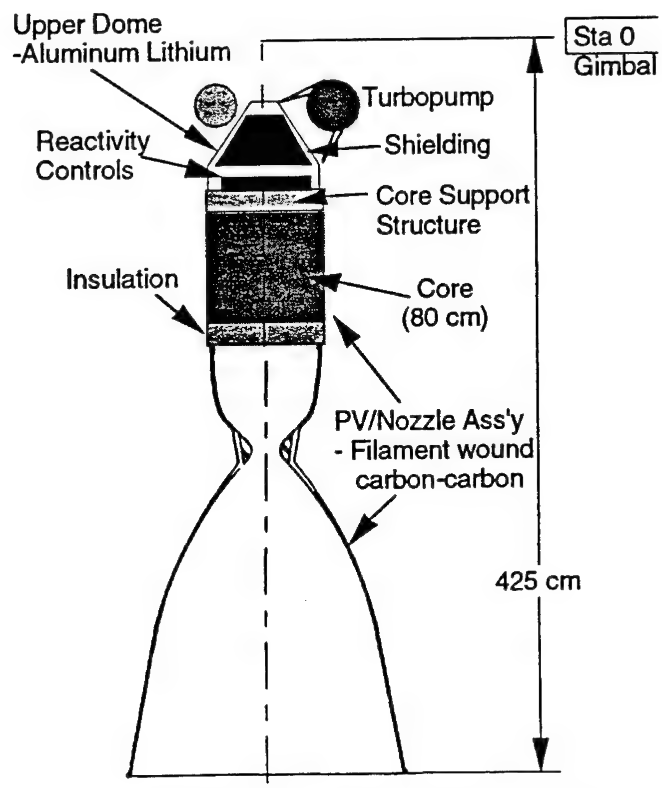


Figure 4.4-6 SNTP Engine System Description

	LV01	LV02	LV03
Thrust level (lbf)	(44,400)	(83,000)	(41,600)
Core Assembly	315	792	475
Reactivity Controls	34	106	34
PV & Nozzle Assy	125	247	207
TPA	50	105	73
PMS	45	85	68
Instrumentation	11	53	17
TVC	41	63	35
Total (kg)	621	1451	910
T/We	33:1	26:1	21:1

*15% contingency is included
Does not include internal shielding mass allocation

Figure 4.4-7 SNTP Engine System Mass Breakdown

Key design issues for the expander cycles were found to be:

- The amount of energy that could be extracted from the moderator and reflector.
- Thermal stresses produced in the moderator.
- Moderator coolant flowpath sizing effect on pressure drop, neutronics and core size.

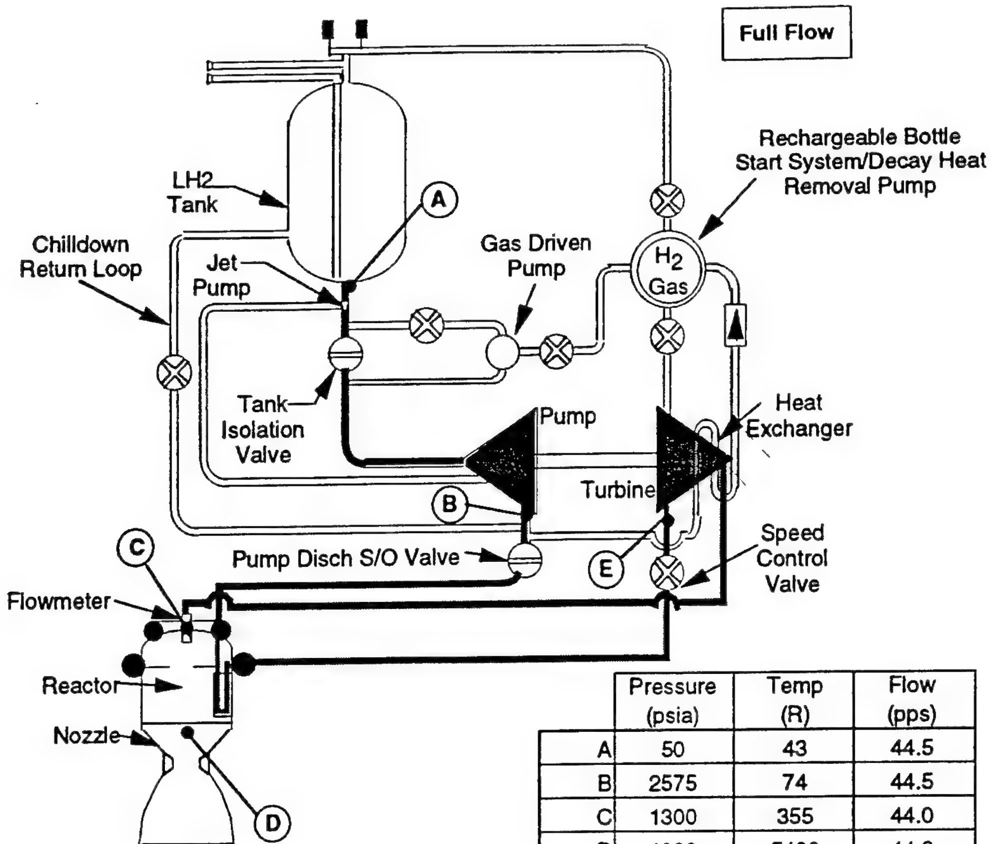
The results of the design calculations showed that the full flow expander cycle required a pressure drop budget of 1000 psi, in order to keep coolant passages to a size required for neutronic performance. This was undesirable for the turbomachinery, which would have to provide >3500 psi, and unacceptable from internal structural considerations. The full flow expander cycle was therefore eliminated from further consideration.

Two partial flow options were studied. One, wherein the turbine energy is derived from the moderator/reflector, and the second, where the turbine energy is provided by flow heated by dedicated fuel elements. Findings from finite element thermal-structural analyses of the moderator and reflector were that:

- Thermal stresses limited the energy extraction to a marginally acceptable value
- Turbine bypass flow was limited to 5%, which is inadequate for TPA control.

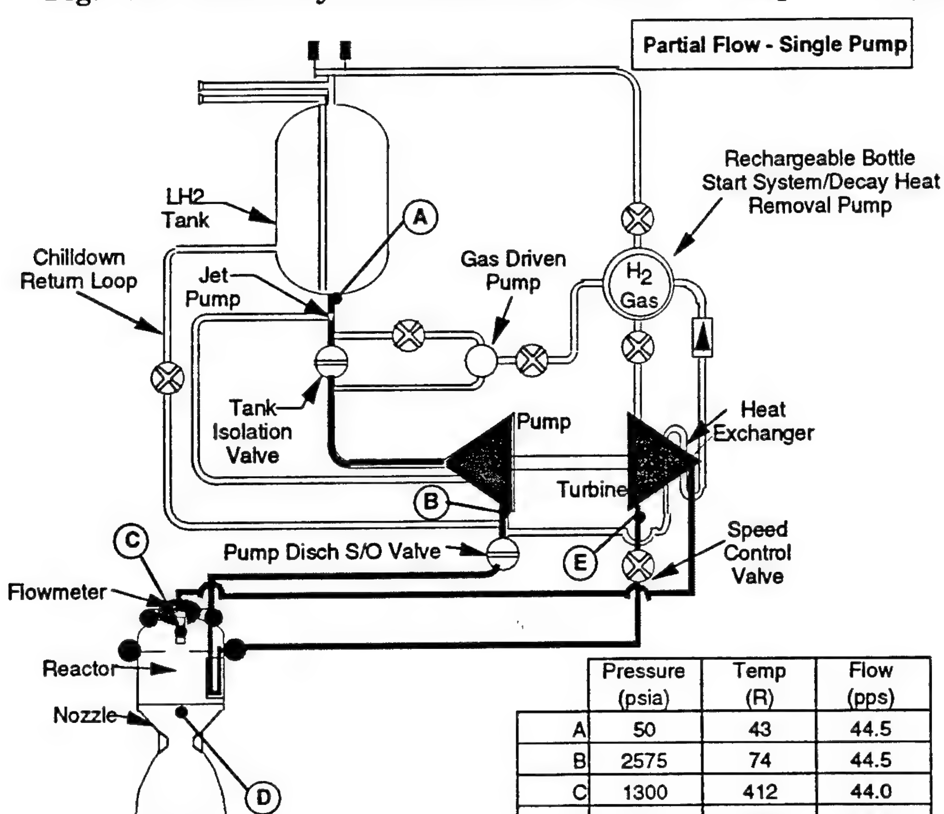
Cycle	TPA Power Source	Reactor Configuration	TPA
Bleed Expander - Full Flow Expander - Partial Flow	Hot Gas Bleed Hot Gas Bleed w/Mixer Reactor Internals Outer Fuel Elements Internal Heat Exchanger	Solid Moderator Water Moderator	1 & 2 Stage Pumps Turbine Inlet Temp: Expander 219 - 1500K Bleed 900 - 2750K

Fig. 4.4-8 SNTP Engine Trade Study Matrix



	Pressure (psia)	Temp (R)	Flow (pps)
A	50	43	44.5
B	2575	74	44.5
C	1300	355	44.0
D	1000	5400	44.0
E	2275	395	44.0

Fig. 4.4-9 SNTP System Schematic: Full Flow Expander Cycle



	Pressure (psia)	Temp (R)	Flow (pps)
A	50	43	44.5
B	2575	74	44.5
C	1300	412	44.0
D	1000	5400	44.0
E	2275	675	11.5

Fig. 4.4-10 SNTP System Schematic: Partial Flow Expander Cycle

Based on the above results the second option of using dedicated fuel elements was pursued. Neutronic and thermal-hydraulic analyses of the reactor were performed, which concluded with a viable design. The characteristics of this design are compared to that for the bleed cycle in Figure 4.4-11. At this point an assessment of the two designs was planned, but was not performed due to program termination.

A summary of the pros and cons of the two systems is given in Figure 4.4-12. Since the factors are all qualitative, it is difficult to reach any conclusions as to which system would have been selected for further development in the SNTP program. One conclusion is clear; the expander cycle would reduce the development risk of the TPA and turbine feed system, but would have increased the reactor development risk. The impact on the programmatic risk remains unclear.

4.4.3 Reactor Subsystem

The reactor subsystem development followed that of the engine, described above. Various concepts and configurations were investigated and analyzed as the missions changed and requirements were revised. The last design developed was for the LV03 engine, albeit a smaller reactor was being investigated at programs end. This smaller configuration (LV04) was being pursued to reduce the Demonstration Engine test cost, and will be discussed later.

Performance and Design Requirements

The requirements imposed upon the reactor subsystem are shown in Figure 4.4-13. In addition to the obvious challenges of high mixed mean outlet temperature, high power density and low mass, operation after long coast periods requires efficient removal of decay heat, and maintaining structural and functional integrity of the subsystem. This imposed a significant design problem, since in order to minimize system performance penalties, the coolant is required to exit the reactor at the highest temperature possible. Furthermore, an additional safety consideration was introduced; i.e., in addition to precluding inadvertent criticality the design was required to exhibit a negative power coefficient over its entire operating range.

Reactor Characterisitics and Mass Properties

Lessons learned from previous designs (LV01,02) and several design iterations were performed to develop a configuration that for the most part satisfied the requirements shown in Figure 4.4.-13. Key design parameters were found to be fuel element pitch to diameter ratio and materials used in the core. Neutronic performance, reactor mass and feedback coefficients were directly related to these parameters. In addition, there was also a large impact on nozzle weight since the nozzle inlet section was sized by the reactor core diameter .

Early designs (LV01, 02) used a polyethylene/aluminum matrix as the moderator material, and sintered aluminum for the cold frit. These materials were inadequate to withstand the high temperatures that would be experienced during the coast/decay heat removal mode of operation, and higher temperature-capable materials were evaluated for these components. In addition to the materials investigations, the sensitivities to pitch, the number of fuel elements and feedback coefficients were determined to arrive at the selected LV03 baseline configuration.

	Bleed Cycle	Partial Flow Expander Cycle
Reactor Power, MWt	1000	1000
Engine Thrust, Lbf	41,385	41,610
Isp, sec	930	935
Reactor:		
•Chamber Temp, K	3000	3000
•Chamber Press, psia	1000	1000
•No. Fuel Elements	37	37
•Reflector Mat'l	Beryllium	Beryllium
•Moderator Mat'l	Be/Li-7H	Be/Li-7H
TPA Power Source	Chamber Bleed	(3) Dedicated F.E.'s
Pump:		
•Type	Single Stg/Centrif	Two Stg/Centrif
•Material	Aluminum	Aluminum
•Disch Press, psia	1350	2575
Turbine:		
•Type	Two Stage	Two Stage
•Material	Carbon-Carbon	Titanium
•Pressure Ratio	15:1	1.75:1
•Inlet Press, psia	850	2275
•Inlet Temp, K	2750	375
Nozzle/Pressure Vessel		
•Type	Radiation Cooled	Radiation Cooled
•Material	Filament Wound C-C	Filament Wound C-C
•Exit Area Ratio	100	100

Figure 4.4-11 Characteristics of Bleed and Partial Flow Expander Cycles

	Pro	Con
Bleed Cycle	1. Lowest system complexity 2. Minimum reactor internal plumbing & manifolding 3. Development of reactor and balance of plant (BOP) is uncoupled 4. Fast startup easily achieved	1. Development of high temp turbine and feed lines required
Partial Flow Expander Cycle	1. State of the art turbine technology can be used 2. Higher I_{sp} (~0.5%)	1. Coupled reactor and BOP development increases programmatic risk 2. Dedicated fuel elements to supply energy to drive the turbine are of unique design and require additional development

Fig.4.4-12 Comparison of Bleed and Expander Cycles

Power	1000 MWt
Outlet Temperature	3000 K
Outlet Pressure	1000 psia
Average Power Density	40 MW/l
Firing Time:	
•Full Power	600 sec
•Full Power +20% Power	500+700 sec
Number of Starts	3
Startup Time to 100%	10 sec
Throttle Operation:	
•Turndown	5:1
•Outlet Temperature	2700 K
Coast Phase:	
•Maximum Coast	5.5 hrs
•Minimum Coast	600 sec
•Outlet Temperature	1100-1500 K
Mass Bogey	310 kg

Figure 4.4-13 Reactor Requirements

The sensitivity calculations and determinations of feedback coefficients were used to select the final LV03 configuration. Based on these analyses, it was decided to concentrate on a reactor with 37 elements, which had a solid moderator, and could operate in a decay heat removal mode. The analysis was carried out by varying the fuel element pitch, while maintaining the value of k_{eff} at 1.1. by changing the reflector thickness. Results of this analysis are shown on Figure 4.4-14. Mass is insensitive to element pitch, with a flat minimum occurring between 9.0 cms. and 10.0 cms. Reductions in reflector mass with increasing pitch are compensated for by simultaneous increases in moderator mass. These calculations were performed for the stainless steel cold frit which was required for the high temperature experienced during decay heat removal. The minimum mass from Fig. 4.4-14 is 800 kg, which was too heavy to meet the thrust/weight goal. To achieve a significant mass reduction, the poisoning effects of stainless steel cold frits were eliminated. This was accomplished by replacing the stainless steel frits with beryllium frits. Beryllium has a negligible absorption cross section, and a significant (n,2n) cross section. The use of beryllium for cold frits had been ruled out earlier in the program due to manufacturing difficulties, but a later assessment concluded that beryllium cold frit manufacturing processes could be developed in the time frame consistent with other flight engine technology development.

A sensitivity study examined the variation of reactor mass for the two cold frit types and for various average bed uranium loadings for a constant pitch. Results are shown on Figure 4.4-15 for a pitch of 9.025 cms. Using beryllium, reactor mass was reduced by approximately 325 kg to a total mass of 475 kg. Furthermore, the average uranium loading would be in the range .85 gm/cc - 1.1 gm/cc. This fissile loading requirement had implications for fuel particle temperature capabilities as discussed later. The results shown in Figure 4.4-15 are a summary of the results shown in Figure 4.4-16, which show how k_{eff} varies with radial reflector thickness for various cold frits, and fuel element pitches. Configurations with a value of k_{eff} =1.1 and a pitch of 9.025 cms. require a reflector thickness of 2.26 cms. and 0.95 cms. for the two fissile loadings. For the reactor with a pitch of 9.6 cms., no reflector is required. In

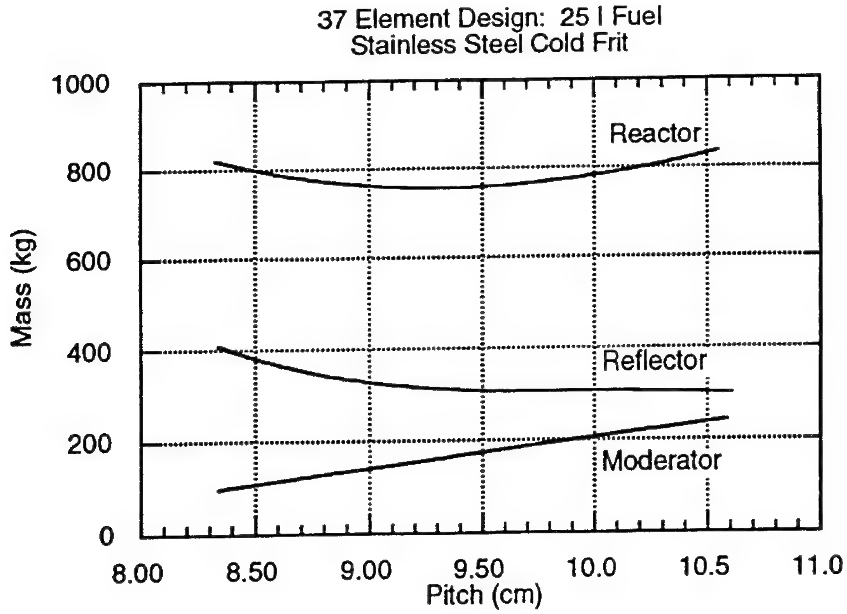


Fig. 4.4-14 Reactor Mass vs. Pitch with Constant $k_{eff} = 1.1$

fact, for the higher fissile loading, the value of k_{eff} is always above 1.1. The lowest mass reactor has the smallest pitch and the highest average fissile loading in the fuel bed. This occurs because the reactor has the lowest diameter core. Since the mass of the pressure vessel, inlet and outlet plena, and reflector are all strong functions of the core diameter, these are automatically minimized. The above resulted in the LV03 reactor characteristics shown in Figure 4.4-17. Figure 4.4-18 is a typical reactor assembly, including the safety and control devices.

Optimizing mass required a reflector thickness of approximately 1.0 cms, which required that the reactor controls be located in the core, rather than in the reflector.

Fairly detailed analyses of the reactor feedback coefficients and control characteristics were completed. In addition to being essential to the reactor design, these analyses were used to evaluate compliance with the design goal of negative power coefficient over the entire operating range. It was clearly demonstrated that the prompt feedback coefficient would remain negative throughout the entire range, due to the Doppler effect. However, the overall power coefficient was positive, with the feedback at hot conditions being lower than at the cold start up. This is desirable in the PBR because the large reactivity insertion due to the introduction of cryogenic hydrogen, is balanced by the positive feedback of the cooled moderator, in effect making the start up easier to control. It was also shown that the time frames in which excursions due to the positive power coefficients could occur are slow relative to the capability of modern computer controlled systems. At the conclusion of the design and control studies it was the consensus of the Reactor Design Team and the Program that the design would meet all DOE safety requirements, albeit not the original design goal of a negative power coefficient over the entire operating range.

The above analyses were performed for a fuel particle being developed by the Program, known as the Infiltrated Kernel (IK) particle. This particle was potentially the lightest and

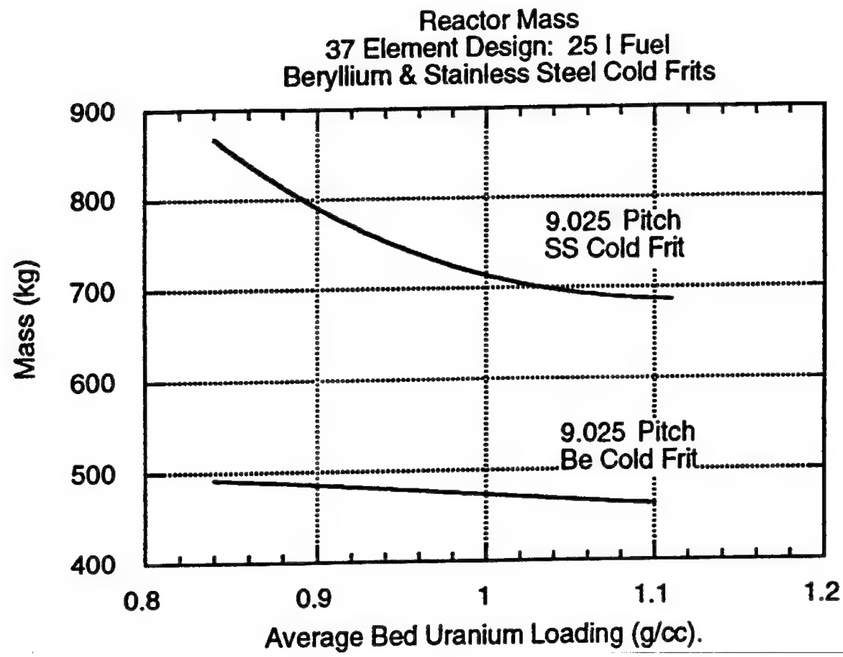
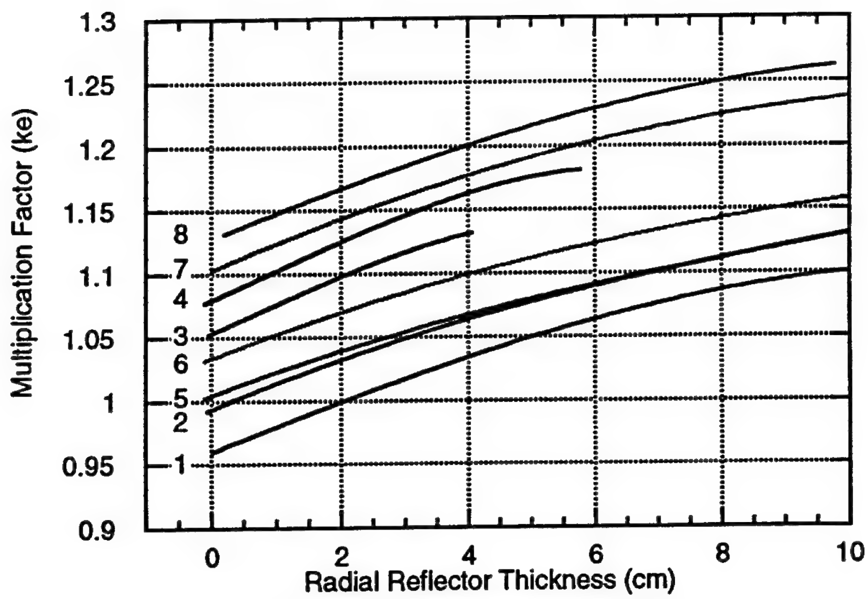


Fig. 4.4-15 Reactor Mass vs. Uranium Loading



ID	Cold Frit	IK Fuel Loading (g/cc)	Pitch (cm)
1	SS	0.853	9.03
2	SS	1.109	9.03
3	Be	0.853	9.03
4	Be	1.109	9.03
5	SS	0.853	9.6
6	SS	1.109	9.6
7	Be	0.853	9.6
8	Be	1.109	9.6

Fig. 4.4-16 Multiplication Factor vs. Radial Reflector Thickness for Various Cold Frit Materials and Uranium Content

Number of Fuel Elements	37
F.E. Pitch	9.025 cm.
Core Diameter	63.175 cm.
Core Height	63.175 cm.
Reflector Thickness	0.95 cm.
Materials:	
Reflector	Beryllium
Moderator	Beryllium/Li-7H
Cold Frit	Beryllium
Hot Frit	Carbon-Carbon/TaC Coating
Fuel:	
Type	Infiltrated Kernel
Bed Volume	25 liters
Fuel Loading	1.11 kg/l

Figure 4.4-17 LV03 Reactor Characteristics

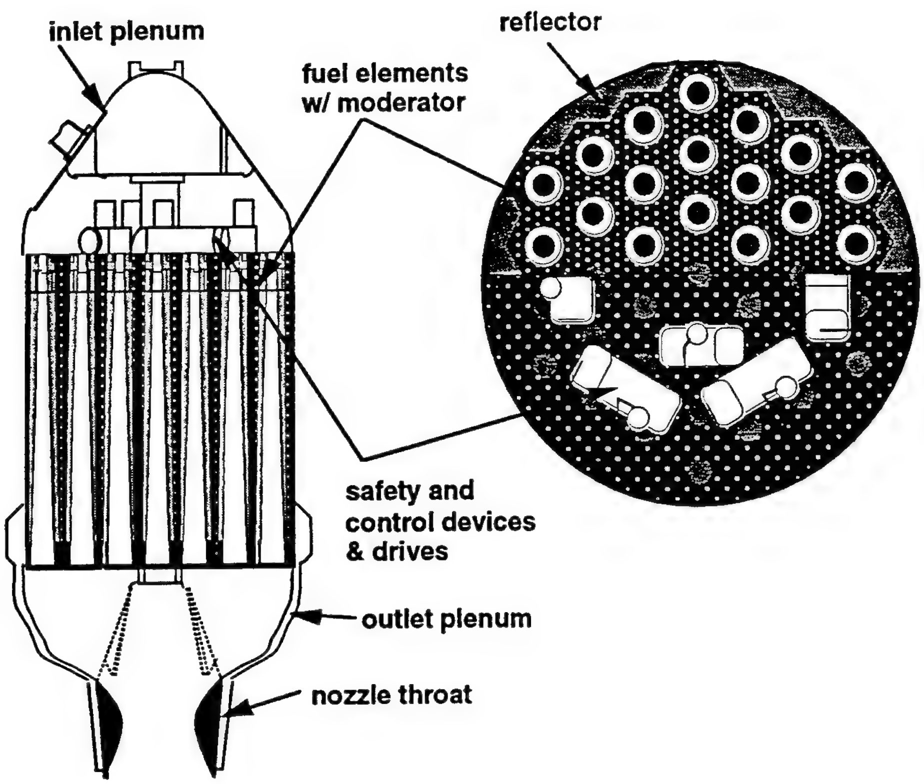


Figure 4.4-18 Typical Reactor Assembly

highest performing compared to Mixed Carbide Fuels (MCF) which were also being investigated. Visibility into fuel technology developments in the Former Soviet Union (FSU) caused the Program to reassess the approach of developing the IK particle and, for reasons of reduced risk, to go forward with MCF development based on FSU technology. Further discussion on the fuel assessment can be found in Section 4.5. A cursory review was made to identify the possible ramifications of the MCF on the LV03 design.

The LV03 design imposed both temperature and fissile loading requirements on the fuel particle. The hottest fuel particle in the bed would have to survive 3500 K in order to attain a mixed mean outlet temperature of 3000 K, the design requirement. In the case of a MCF composed of (U,Zr)C, the uranium content could be limited in order to remain below the solidus at 3500 K operating temperature. This in turn could require increased fuel bed volume (and mass) to attain criticality. In addition, the basic density of the MCF particle is approximately 40% greater than the IK particle, compounding the weight penalty. At program's end these effects had not yet been addressed, so the potential impact is not quantified.

Safety Features

The nuclear safety design requirements were:

- Preclude inadvertent criticality.
- Preclude sustained criticality if immersed in water or other fluids.
- No nuclear operation prior to mission operation, other than zero power testing.
- Fail safe throughout mission timeline.

Redundant safety features were incorporated to meet these requirements. Cones of poison material (consisting of B_4C) would be inserted in the hot frits and remain there through the launch and separation of the upper stage. The negative reactivity of these cones was sufficient to keep the reactor subcritical, even in a water (or other fluids) immersion accident. After removal of the cones, the Bistem devices would keep the reactor subcritical while they remain in the core (their position at launch). After the Bistems were withdrawn the reactor could be started up, with shut down effected by reinsertion of the Bistems. Backing up the Bistems in the event of their failure to shut down the reactor, was a boron injection system, wherein boron powder would be injected utilizing pressurized helium. The boron would coat the fuel and other components of the reactor, permanently poisoning it and rendering it inoperable.

Critical Experiments (CX)

An issue raised early in the program was the ability to accurately calculate the internal neutronics of the particle bed reactor (PBR). The reason for this concern was that the compactness, thermal spectrum and extreme heterogeneity of the PBR was expected to produce very non-uniform neutron flux and power distributions within the reactor. To obtain optimum performance, it was necessary to accurately predict internal power distribution to enable matching coolant flow and obtain a uniform hydrogen temperature exiting at all points of the fuel beds.

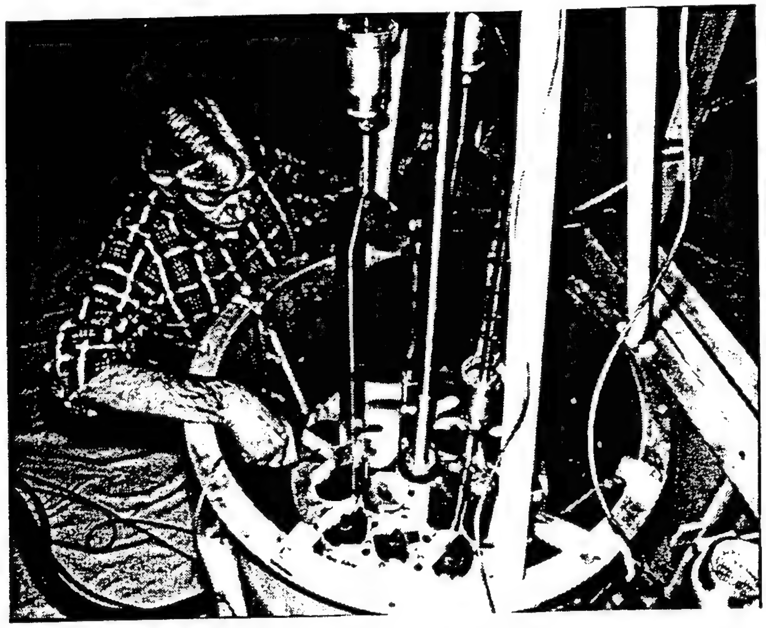


Figure 4.4-19 Critical Experiment Reactor

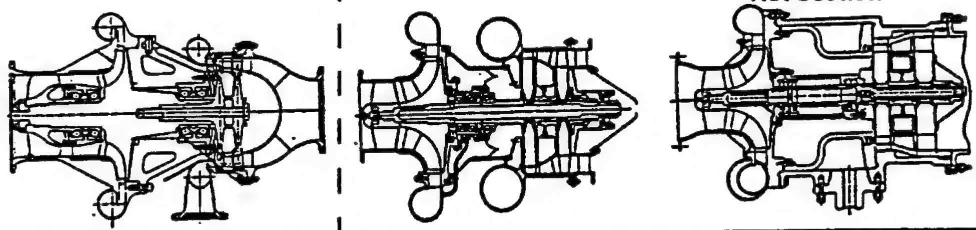
A decision was therefore made to perform a zero power critical experiment (CX) to study the internal neutronic behavior of the PBR. A successful series of experiments were run in the Sandia National Laboratory (SNL) Tech Area V, with a 19 element configuration that was neutronically representative of the early PBR design(LV01). Analytical methods of predicting the neutronic performance were developed, and the results were compared to the experimental data. The agreement of analytical and experimental results was extremely good (within 0.5%), providing the confidence needed for the design process. The CX was then used to obtain basic design data, e.g., reactivity worth of critical reactor components.

In addition to the technical accomplishments and data obtained from the CX, the Program took considerable pride in preparing the CX Safety Analysis Report and obtaining DOE approval to operate the reactor. The CX was the first reactor approved for operation by the DOE in over ten years. Figure 4.4-19 is a picture of the CX reactor.

4.4.4 Turbopump Subsystem

The turbopump assembly (TPA) design evolution was driven by obtaining higher engine performance and lower system mass. Initial requirements to improve performance obtained in Phase I led to higher turbine inlet temperature, and cooled metal turbine configurations. Problems due to internal body heating from the radiation environment led to a carbon-carbon rotor configuration. It was a logical step from there to an all carbon-carbon turbine hot section with higher temperature capability and increased system performance. A carbon-carbon turbine design was developed, and demonstration of the technology was underway at program's end.

The evolution of the TPA design is summarized in Figure 4.4-20.



	Phase I	Phase II	
	All Metallic	Metal Case/ 1. Cooled wheel 2. C-C wheel	All Carbon-Carbon Hot Section
Turb Inlet Temp	900 K	1555 K	2750 K
Weight	80 Lbm	80 Lbm	65 Lbm
Thrust	40 Klbs	80 Klbs	40 Klbs
Δlsp	0 Sec	+14 Sec	+22 Sec
Neutronic Heat Eff.	Acceptable	1. Unacceptable 2. Acceptable	Acceptable

Fig. 4.4-20 Turbopump Assembly Evolution

Configuration Development and Mass Properties

The major TPA design driver was found to be internal nuclear heating of the turbine rotor disk, which had a maximum rate of 30 W/cc. This combined with operation in the hot hydrogen environment, made the TPA development risk high. The risk mitigation approach was to reduce operating temperature as necessary, providing substantial risk reduction with acceptably low performance penalty.

Early thermal-structural analyses of the cooled rotor configuration showed that due to internal nuclear heating, the first stage turbine rotor disc developed unmanageable thermal stresses. The combined stresses could not be reduced by increasing part thickness, since it would increase the thermal stresses. After reviewing the options, it was concluded that a low "Z" structural material was needed if 1500K turbine inlet temperature was to be achieved. The material selected for the rotor was a 2-D polar weave carbon-carbon. The reasons for this selection were:

- Carbon-carbon has a superior neutronic cross section which results in much lower nuclear heating than other candidate materials, as shown in Figure 4.4-21.
- Hercules Composite Structures Division, as part of the SNTP design team, was developing the carbon-carbon nozzle using a new ultra high modulus fiber (UHM) that promised to improve strength by 50%.

- Allied Signal Fluid Systems Division (FSD) had successfully designed, built and demonstrated a 2-D polar weave carbon-carbon turbine for turbojet application (ELITE Program).

A number of metallic static section configurations were studied for the 1500 K design, and were found to be fairly complex. A preliminary assessment of a 3-D carbon-carbon static section indicated that a viable design could be developed. This would allow turbine inlet temperature in excess of 2500 K, eliminating the need for a bleed mixing and control system, and improving system performance. The material here was essentially the same as that being developed by Hercules for the nozzle, so that programmatically the development risk was not substantially increased. The decision was therefore made to pursue the development of a carbon-carbon turbine hot section design.

The design was completed through an internal preliminary design review (IPDR), and the salient features are shown in Figure 4.4-22. The design incorporated a jet pump into the TPA pump inlet. This eliminated the need for a booster pump to handle the hydrogen flowing at saturated conditions due to nuclear heating to the propellant tank.

In addition to the conventional design and development issues, e.g., aerodynamics, rotor dynamics, shaft bearings and seals the carbon-carbon turbine had unique development issues. These issues and planned resolutions are described below:

Material	Heat Rate (W/cc)	Max Temp (K)	Applications
Inconel	91	1100	SSME/XE-P (Nerva): (housings, shafts, seals)
Waspaloy	105	1100	SSME: turbine rotors (1105K)
A286	82	1100	XE-P/MMII phase I: turb rotors (648K/900K)
Titanium	44	1120	SSME/XE-P: (inducers, spacers, etc.)
Niobium	83	1150	housings, etc.
C-C	15	2750	ELITE: turbine rotors (1950K)
Aluminum	20	500	Pump impellers, housings, etc.
Copper	86	650	heat transfer devices

Fig. 4.4-21 TPA Materials in LV03 Nuclear Environment

• Rotor Shaft Bearings and Seals

Issue: Historically turbomachinery rotor bearings and seals have caused serious problems in nearly every pump-fed liquid rocket engine development. This problem was exacerbated by the nuclear environment in which these components must survive.

Resolution: Use of Allied Signal's cooled metallic roller bearings which do not employ radiation sensitive materials, and grafoil seals which have been demonstrated to be acceptable in a radiation environment.

• Carbon-Carbon Rotating Components

Issue: High temperature, highly stressed turbine rotors operating in a corrosive and erosive atmosphere.
2D polar weave architecture has low interlaminar properties.
Carbon-carbon material requires protection from the hot hydrogen gas.

Resolution: A program to develop a highly integrated rotor architecture using high strength UHM carbon fiber was in progress.

A High Temperature Spin Rig (HTSR) was designed to evaluate the turbine rotors at design temperature and rotational speed. A series of tests was planned to gradually subject the rotors to more stringent conditions from cold spin with inert gas to design conditions with hydrogen.

Refractory metal carbide coatings were being developed to protect the carbon-carbon material from the effects of hot hydrogen.

• Carbon-Carbon Static Components

Issue: Four carbon-carbon static structure parts were required to contain the hot, high pressure hydrogen gas for the flow path through the TPA turbine section. As with the turbine rotors, these parts had to withstand the temperature, stress, and the corrosive and erosive effects of the hot hydrogen gas.

Resolution: Each carbon-carbon static structural component was carefully designed with the appropriate carbon-carbon architecture chosen to accommodate its requirements.

The aforementioned HTSR used to evaluate the rotors was also to be used to demonstrate the integrity of the static structure as a complete turbine stage assembly.

Coatings developed for the rotors, or variants thereof, would likewise have been used to protect the static structure components.

• High-Temperature, Static Seals

Issue: Two of the static structure components formed a high pressure vessel assembly which was sealed by graphite O-ring like compression seals. The integrity of these seals was critical to the successful operation of the turbopump.

Turbopump Assembly:	
Speed (100% Thrust)	55,600 RPM
Burst Speed (SF 1.25)	69,500 RPM
Power	6263hp
Shaft Material	Titanium
Bearings	Roller Bearings
Mass	73 kg
Pump: Single Stage Centrifugal Pump with Inducer, Internal Jet Pump and Thrust Balancing	
$NPSH_R$	0 psi
Discharge Pressure	1350 psia
Efficiency (@100%)	72%
Materials: Aluminum Impeller and Housing	
Turbine: Two Stage Reaction Turbine with Disk Face Cooling	
Inlet Pressure	850 psia
Discharge Pressure	50 psia
Inlet Temperature	2750 K
Tip Speed	1787 fps
Efficiency (@ 100%)	27%
Materials:	
Polar Weave UHM Carbon-Carbon Rotors	
3D UHM Carbon-Carbon	

Fig. 4.4-22 TPA Features

Resolution: The seal configuration chosen was one that has been successful in applications similar to this and the design for the turbopump had carefully taken into account the critical parameters of its incorporation.

A static test rig had been conceived to simulate a typical critical seal location. The rig, made from carbon-carbon, could be pressurized and leakage, if any, measured.

- High-Temperature Fasteners

Issue: The static structural components were designed to be fastened to each other using carbon-carbon fasteners since these components will be operating at extremely high temperatures. Threaded studs and nuts were the fastener configuration of choice. There is not a broad base of experience using carbon-carbon threaded fasteners.

Resolution: There is much design and research test data in the literature for designing with carbon-carbon threaded fasteners and this information was being used to optimize the fasteners for the turbopump.

The components of the test rig used for testing the seals were to be fastened with the subject carbon-carbon fasteners and thus would have received an initial room temperature test.

The HTSR would have likewise utilized the carbon-carbon fasteners.

It is believed that the TPA development plan utilizing the HTSR would have resulted in the successful development of the carbon-carbon hot section.

Carbon-Carbon Turbine Fabrication Development

It was essential to develop the fabrication processes for the 2-D polar weave carbon-carbon rotor. Unlike the 3-D carbon-carbon static sections where Hercules had sufficient fabrication experience, it was expected that process development for the rotor would be extensive. Using design techniques developed at Allied FSD (for ELITE), a sophisticated dual polar weave architecture configuration was developed for the turbine rotor, using Hercules UHM fiber. Allied FSD subcontracted the weaving of the preform to Woven Structures Division of BP Chemicals, Inc. and subcontracted the processing of the rotor blanks to Rohr Industries, Inc.

Thirteen (13) design iterations were required to reach an optimized weave architecture. In the interim a non-optimized preform was fabricated in order to start the process development. Early efforts using a ten (10) layer stack of dry laminates impregnated with phenolic resin resulted in excessive fiber volume content.

Compression molding (CM) trials were made to improve the fiber volume and explore cure and post-cure process parameters (pressure, temperature, time, viscosity , etc.) A full thickness (1.6 in) laminate was compression molded and processed. Voids were found to be present, which was probably due to excess volatiles and resin shrinkage. At this point CM efforts were put on hold and resin transfer molding (RTM) trials were begun. It was felt that RTM would produce a better product for a non-uniform preform such as the turbine rotor.

The initial RTM blank was processed and exhibited exceptional consolidation throughout the part. However delaminations occurred indicating high mechanical stresses arising during the cure. A second RTM blank was fabricated with a revised design and some modification of the cure cycle. Delamination again occurred, this time during the post-cure cycle. The post-cure process was revised, so as to dwell at a temperature below the glass transition temperature. This process was applied to a third RTM blank, but delaminations again occurred. At this point the history and all the data were reviewed, and a plan to develop a hybrid process (RTM and CM techniques) was recommended.

Program funding for further carbon-carbon turbine rotor development was halted in this time frame. Rohr, as part of their company IR&D, initiated development of a hybrid process. After three tries, using a non-prototypic fiber (8SH T300), a full thickness blank was processed exhibiting acceptable properties and having no delaminations. The status at the end of this effort was that a viable process for fabricating the carbon-carbon rotor blank was partially demonstrated, with the next step being demonstrating the process using the UHM fiber.

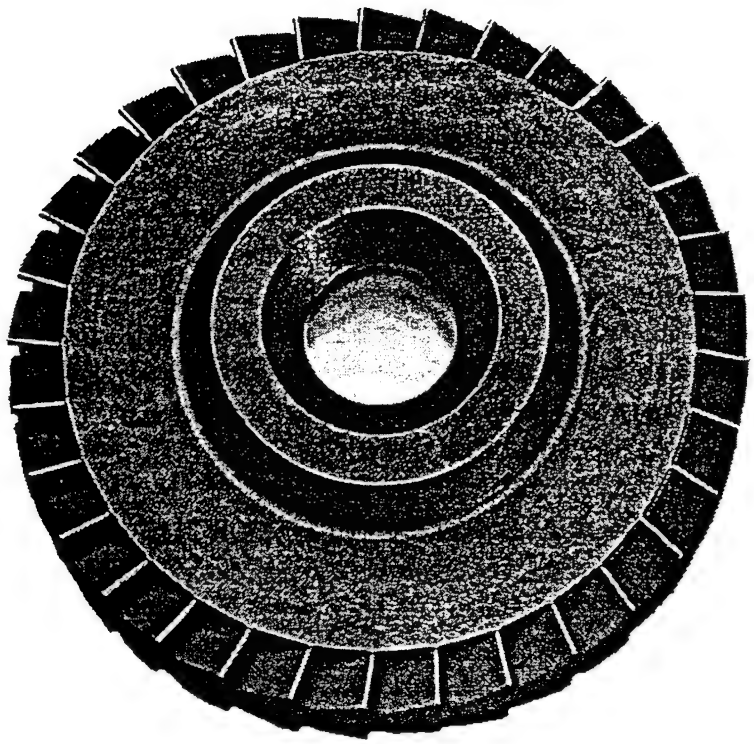


Fig. 4.4-23 Graphite Turbine Wheel

In addition to carbon- carbon processing, the tools required for machining the blanks into integral rotors was also being developed. In order to keep costs to a minimum, graphite was used for tooling development instead of the composite material. Five graphite rotors were successfully machined by Southern Graphite, Inc. Figure 4.4-23 is a photograph of one of the machined graphite wheels.

4.4.5 Propellant Management Subsystem

The Propellant Management Subsystem (PMS) consisted of the liquid hydrogen feed from the propellant tank to the reactor inlet, turbine hot hydrogen gas feed and discharge, tank pressurization, and start system. The subsystem and its' components are shown in the schematic flow diagram, Figure 4.4-3. Due to program (and funding) priorities, the effort on this subsystem was conceptual in nature and was mainly limited to layouts, component configuration and material selection and feasibility assessments.

Except for the flowmeter, the technologies for the components on the liquid hydrogen side were well defined. An oscillating jet flowmeter was baselined, because it is accurate over the large turndown ratio required during start up, is reliable (no moving parts), and is insensitive to the radiation environment.

The hot components, which would be graphite or carbon-carbon, would require development to meet the design requirements. Fabrication processes development would also be required, which would draw upon the experience gained from development of the other static carbon-carbon and graphite components being used in the engine. Notably, develop-

ment of the speed control valve (SCV) and the high temperature bleed line flex joints would be challenging. Risk mitigation approaches, e.g., double wall cooled designs, were to be considered.

4.4.6 Pressure Vessel and Nozzle Assembly

The reactor pressure vessel (PV) and nozzle assembly underwent significant concept and design evolution. The Phase 1 design was a regeneratively cooled metallic nozzle entrance and throat, with a 3-D carbon-carbon nozzle extension. In addition to being too heavy to meet the weight bogey, the design was complex and introduced reliability issues related to the use of segmented carbon-carbon liners. The liner was needed to distribute the convective heating from the impinging gas streams exiting from the reactor hot frits. Segmenting the liner was required to accommodate coefficient of thermal expansion (CTE) mismatch with the metal, and thermal cycling due to engine restarts. An assessment of an all carbon-carbon nozzle was made which showed that a feasible design could be developed which would eliminate the segmented liner, and would be significantly lighter. The Program then baselined the carbon-carbon nozzle.

In parallel, configuration and material studies of the reactor PV were being performed. Due to high nuclear heating only materials that were readily coolable (high thermal conductivity) appeared to be feasible. Aluminum-lithium was initially selected because of its strength, thermal conductivity, and radiation properties. This introduced a difficult dissimilar joint design problem; the widely different CTE's, and the location of the joint near the hot gas region at the reactor outlet.

Configurations were then explored which would integrate the PV and nozzle. A viable design was developed with an integral filament wound (FW) carbon-carbon PV and nozzle assembly. An aluminum-lithium dome at the head end of the engine was required to accommodate the propellant line and control actuator penetrations, thereby retaining the dissimilar joint problem; albeit a less severe one since the joint was located at the cooler head end.

Configuration Development and Mass Properties

As in all the other components, the PV/Nozzle Assembly performance and design requirements were driven by the engine system requirements. The requirements were met with innovative and somewhat unproven, yet simple design concepts.

Pressure vessel and nozzle material options are shown, along with their pros and cons, in Figure 4.4-24. Potential configurations with these material options are depicted in Figure 4.4-25. The requirement for high exhaust gas temperature during the coast/decay heat mission phases could not be met using low temperature aluminum alloys. This was due to the low temperature difference between the PV and reactor core at very low power (<1%). High temperature metals, because they would be subject to severe nuclear heating (see Figure 4.4-21), required internal cooling. In addition, the high temperature metals resulted in heavier configurations (approximately 100% increase in PV/Nozzle Assembly weight). Consequently it was decided to pursue an integral pressure vessel/ nozzle inlet of carbon-carbon construction.

Several configurations were evaluated including three directional (3-D) and filament wound (FW) forms of carbon-carbon. FW carbon-carbon had been demonstrated by Hercules on small scale components, indicating that it could be scaled up to the size required for the SNTP PV/Nozzle. The advantages and disadvantages of the two composite forms are summarized in Figure 4.4-26, and a weight summary of four viable designs is shown in Figure 4.4-27. Based on these results, a FW integral PV/Nozzle Assembly was baselined. The elliptical lower dome (config. 2(b)2) was selected over the lighter weight geodesic configuration (config. 2(b)1) for improved nozzle flow performance.

Thermal analyses of the design indicated that the carbon-carbon material limit of 2750K could be exceeded in the inlet region. Three potential solutions to the problem were identified which were considered viable. These were:

- Use of a high temperature insulating liner
  - applied to the ID of the inlet region to significantly reduce the primary structure temperature.
  - applied to the OD of PV and inlet to reduce through-wall thermal gradients and thermal stresses.

- This technology has been successfully used in small diameter solid propellant blast tubes.

- Local film cooling of hot areas requires < 0.3% coolant. This technology is well known, but new to carbon-carbon.

- Extend the temperature range for carbon-carbon as a primary structure
  - requires allowable temperature increase of 250 K.
  - current material limits are related to elastic stability at high temperature, which are related to composite processing temperature and fiber processing conditions. Preliminary results of processing at temperature > 3000 K show that strength would be unimpaired and fiber creep rate could be reduced.

These approaches all appeared to be promising, and it was planned to further pursue them and evaluate impacts on cost, development risk and performance. Figure 4.4-28 shows the nozzle arrangement.

Joint Design

As previously discussed, the joint location was selected to be at the head end of the engine, where the FW carbon-carbon PV is joined to the Al-Li dome. Not only was this joint required to transfer the thrust load from the nozzle to the thrust structure, but it was also required to be leak tight and maintain it's structural integrity throughout a wide range of thermal conditions. Start up from below room temperature to operating temperature of the joint (350 K) would cause displacements and stresses due to the CTE mismatch. In addition to these design problems, sealing materials used had to be resistant to radiation damage.

Pressure Vessel Options	Nozzle Options
• Aluminum alloys Low weight Surface cooled Low temp during cooldown	• Carbon-Carbon (radiation cooled) Low weight Easiest to integrate with engine Requires coating Properties above 2750K are unproven
• Carbon-Carbon Low weight Surface cooled Hightemp during cooldown	• Inconel/NARLOY (Regen) High weight Proven technology (SSME) Increased reactor inlet temp Higher pump pressure Isp loss Limits temp during cooldown
• Inconel/Titanium/Steels Higher weight Requires internal cooling Moderate temp during cooldown	• Aluminum/C-C liner (Regen) Low weight Increased reactor inlet temp High risk for multiple cycles Higher pump pressure Ilmits temp during cooldown

Figure 4.4-24 Pressure Vessel & Nozzle Material Selection

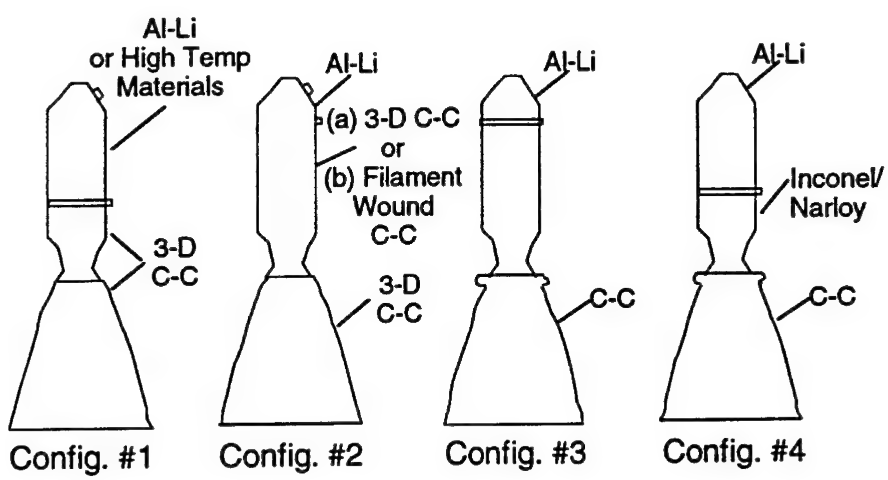


Fig. 4.4-25 – Pressure Vessel/Nozzle Configurations

	Pro	Con

3-Directional Carbon-Carbon	• More mature C-C mfg. and data base
	• Quasi-isotropic properties
	  • More damage tolerant
	  • Higher RA shear
	• More forgiving to densification variables
		• Quasi-isotropic properties
		  • Lower hoop/axial properties
		  • Thicker walls
		  • More permeable
		• More costly to manufacture preforms

Filament Wound Carbon-Carbon	• Higher hoop / axial properties
	  • Thinner walls
	    • Reduced temperature
	    • Reduced weight
	• Large experience base in graphite / epoxy PV's
	• Less costly to manufacture preforms
	• Less permeable
		• Not mature for C-C (some development in 1970's)
		• Not as damage tolerant
		• Lower RA shear/radial tensile properties
		• More sensitive to densification variables

Fig. 4.4-26 Pros & Cons of Two Carbon-Carbon Options

	Weight kg (lb)			
Configuration (Fig. 4.4-23)	#1	#2(a)	#2(b)1	#2(b)2
Component	Aluminum PV 3-D C-C Inlet Low Joint	3-D C-C- PV 3-D C-C- Inlet Upper Joint	FW PV / Inlet Geo. Dome Upper Joint	FW PV / Inlet Ell. Dome Upper Joint
PV	69.3 (153.5)	181.0 (398.9)	97.6 (215.1)	104.0 (229.2)
Inlet	85.8 (189.1)			
Throat	7.8 (17.3)	7.8 (17.3)	6.1 (13.4)	6.1 (13.4)
Exit Cone	87.3 (192.5)	87.3 (192.5)	87.3 (192.5)	87.3 (192.5)
Total	250.5 (552.4))	276.1 (608.7)	191.0 (421.0)	197.4 (435.1)

Fig. 4.4-27 Weight Summary of C-C Design Configurations

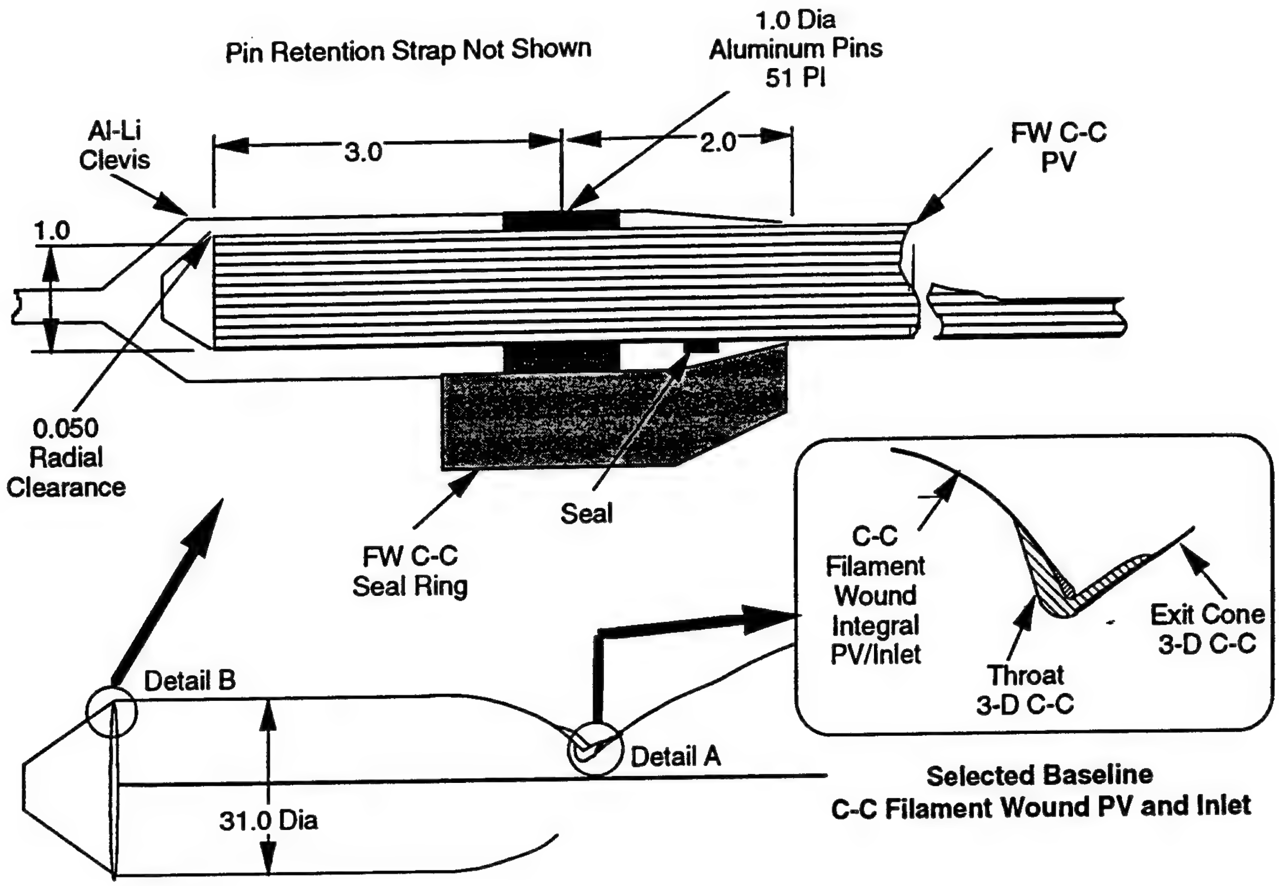


Fig. 4.4-28 Pressure Vessel/Nozzle Layout

Several joint configurations were investigated, including composite tension bands, Al-Li tension tubes and variations of pinned joints. A pinned tang and clevis was selected after thermal, structural and leakage flow path analyses. A single row, pinned Al-Li tang and carbon-carbon clevis configuration was designed which was found to meet all the design and functional requirements. The joint configuration is shown in Figure 4.4-28 (Detail B).

Other Nozzle Efforts

Some of the other significant efforts in the nozzle design process are listed below, with a short summary of findings:

- CFD analyses of the inlet section were performed. The major result of this analysis was to specify an inlet section length- to- diameter (L/D) of 1.0, in order to mitigate the flow mixing losses and nozzle heating due to the impingement of the reactor hot frit exhaust streams on the nozzle wall .

- Radiation effects on carbon-carbon materials properties were investigated via literature search. Relating the literature to the LV03 conditions (temperature, flux, fluence, spectrum and the selected materials) indicate that damage in regions of temperature

> 2000 K was expected to be negligible. Thus the nozzle inlet, throat and exit cone designs should not have been impacted. It was not clear (conflicting data) whether the fluence levels were high enough in the ~1000 second burn to cause damage in the lower temperature regions. In any event the materials properties changes were expected to be small (< 20% reduction in thermal conductivity, and small increases in modulus and tensile, shear and compressive strength).

- Effects of the thermal cycling on the carbon-carbon properties were evaluated based on published data. Thermal cycling of the carbon-carbon components below the processing temperature should have no effect on properties. Coatings were of some concern, however. The most critical region at the inlet would see temperatures exceeding coating deposition temperature. This should cause cracks to close up during the first cycle with some annealing of the coating. This could impact crack closure during subsequent cycles.

- Erosion/corrosion estimates were made which showed that predicted LV03 nozzle recession rates for uncoated carbon were less than that experienced in solid propellant (SPM) uncoated carbon-carbon nozzles. This suggested approaches other than complete reliance on coatings to protect the nozzle. These included sacrificial carbon liners (coated or uncoated) and doping of the hydrogen gas stream with methane. Coating of the nozzle surface would provide additional redundancy.

4.4.7 Demonstration Engine

The purpose of the demonstration engine (DE01) was to demonstrate the SNTP technology using an engine configuration that would be traceable to a flight engine. Initially DE01 was configured as a 1000 MWt Bleed Cycle engine. Because of the Engine Cycle Trade Studies in progress, the engine cycle and the technologies to be demonstrated (e.g., carbon-carbon turbine) were not finalized. In addition the program had embarked on a facility cost reduction program, as described in Section 4.4.7. The impact of that effort was to eliminate the full scale test stands at the Nuclear Ground Test Facility (NGTF), and instead use the PIPET containment as the test bed. As seen in Figure 4.4-29, the PIPET overall dimensions could be maintained for both the bleed and expander cycle 1000 MW_t engine options, but internal changes would be required.

In addition to the physical problems, other interface issues needed resolution, including the following:

- Nozzle back pressure- a nozzle area ratio of 5:1 was desirable but would result in 100 psi inlet pressure in the effluent treatment system (ETS). This was lower than the 300 psi design which would result in a larger (and costlier) ETS.

- Bleed cycle turbine exhaust- the TPA effluent was required to pass through the ETS prior to exhausting to the atmosphere. TPA turbine back pressure was 50 psi, requiring modification to operate at ETS pressure or a pumping system, e.g., an ejector.

- Possible need for external control & shut down systems- this was not resolved, but it was believed that only an external shut down system would be required.

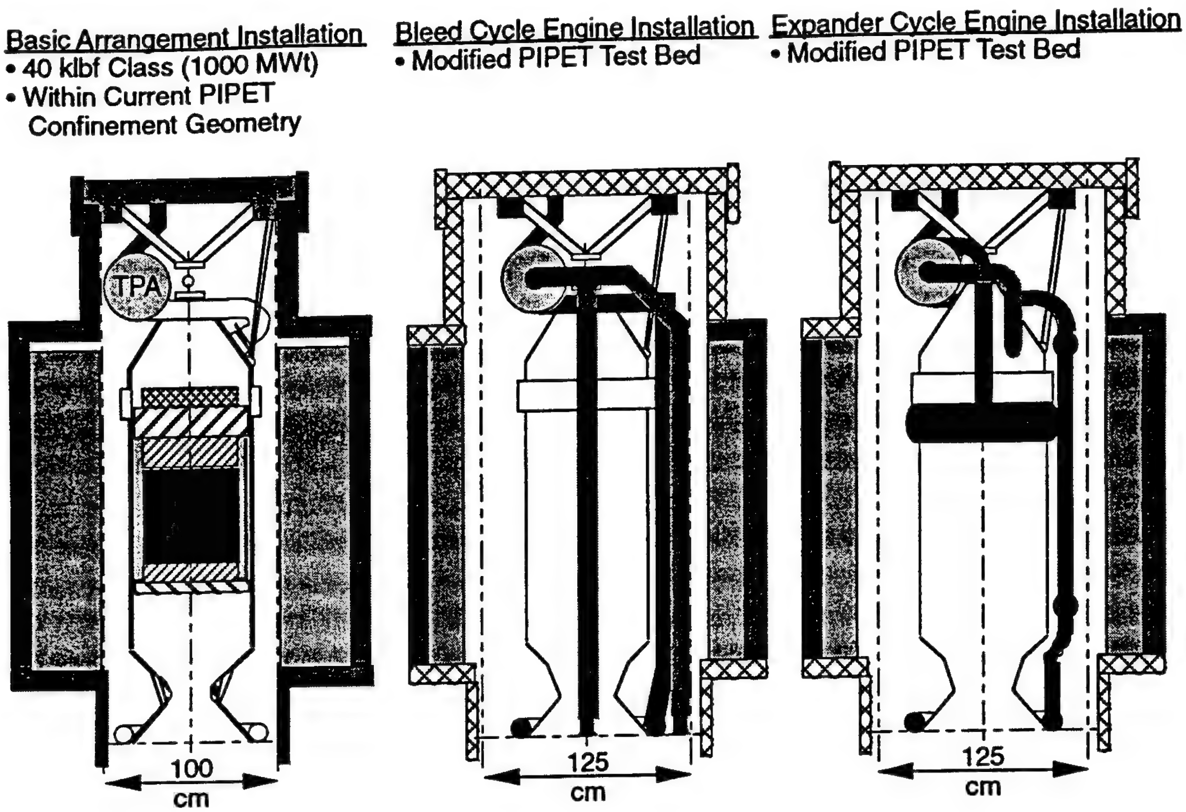


Figure 4.4-29 Demonstration Engine Installation

Near the end of the program a smaller engine design was being investigated. The engine was in the 20 klb thrust class (400 MW_t), and reactor studies were in progress. Early conclusions reached were that a 19 element compact reactor could be made to go critical and exhibit good mass and performance characteristics. To keep the flight engine lightweight, it was necessary to load fissile material into the moderator. Other enhancements were considered that required fissile material in the hot frit exits ("afterburners"). The inclusion of these technologies into DE01 required further study. This engine could have significantly reduced NGTF costs, in that it would have (1) allowed the use of the PIPET ETS (also a 400 MW_t reactor), (2) greatly reduced consumables and (3)reduced potential accident implications.

4.4.8 Conclusions

- The LV03 design met the performance goals set by the mission requirements.
- The bleed cycle met all AF requirements, but required development of a carbon-carbon turbine, carbon-carbon turbine feed lines and a FW carbon-carbon integral PV/Nozzle Assembly.
- The expander cycle that could be best integrated into the SNTP engine was a partial expander cycle powered by three (3) dedicated fuel elements. Development of the aforementioned carbon-carbon components would not be required, but integration with

the reactor could become a significant issue. The reactor internal flow paths would be more complex, and the reactor and turbine developments would have been closely coupled.

- A 40 klb thrust class (1000 MW_t) engine could be demonstrated inside a modified PIPET Test Bed, which could have significantly reduced the cost of the full scale engine ground demonstration. Costs could have been further reduced by testing a 20 klb thrust class (400 MW_t) engine. A viable conceptual design was generated.

- For a constant fuel bed volume, the disadvantage factor became less favorable as the number of fuel elements decreased, while the cost decreased. A 37 element reactor configuration was selected to minimize the disadvantage factor effect, despite a potentially higher cost. Although neutronically superior, a 61 element configuration was discarded due to significantly higher cost. The 37 element configuration was shown to have potential for adaptation if engineering problems arose during the final design.

- Removal of decay heat during coasting periods required a high temperature (1000 K) cold frit. This requirement, coupled with the requirement to minimize parasitic absorption, argued for the use of a beryllium cold frits. Use of stainless steel cold frits would have significantly increasd reactor mass, but would have been an otherwise acceptable fallback if beryllium frit manufacturing processes could not be developed.

- The goal of having a negative power coefficient over the entire operating range did not appear to be feasible for a practical reactor design. However the feedback coefficients were acceptable and would meet all DOE requirements. Specifically;

  - The prompt feedback coefficient would be negative, due to Doppler absorption in the resonances of Ta and U-238.
  - The moderator feedback coefficient , although positive, could result in excursions which would be readily controllable with computer controlled systems.

- The fuel evaluation panel recommended down-selection to the mixed carbide fuel type. This had the following implications:
  - At goal operating temperatures (U,Zr)C was limited to a lower fissile content in the fuel particles. This would require a greater fuel bed volume.

  - Mixed carbide fuels were more dense than the IK based fuels used in the LV03 reactor. Using carbide fuels would result in an increase of almost 10% in reactor weight for the current LV03 design.

- Zero power critical experiments (CX) were successfully run which correlated exceptionally well with the neutronics codes, and provided the confidence to accurately predict the internal flux distribution.

- High performance lightweight carbon-carbon TPA turbine design was developed that met all the requirements. Process development for the turbine rotor was in progress, and a relatively prototypic rotor wheel blank was successfully fabricated.

- An innovative FW carbon-carbon integral PV/Nozzle Assembly design was developed. The design best met system requirements (mass, performance, high coolant temperatures during coast/decay heat mode). FW carbon-carbon had been previously demonstrated on small scale components, indicating that it could be scaled up to the size required for the SNTP PV/Nozzle.

4.5 WBS 1.5 Fuel Development

4.5.1 Overview

The development of a high-temperature particle fuel was one of the major efforts of the SNTP Program. The ultimate goal of WBS Element 1.5, Fuel Development, was to develop a coated nuclear fuel particle with a diameter of approximately 500 μm that would support a mixed-mean hydrogen exhaust temperature of 3000 K when incorporated into a Particle Bed Reactor-based nuclear thermal rocket (NTR) system configuration. This requirement indicated a maximum nuclear fuel particle temperature in the range of 3100 to 3500 K based upon a power density of 40 MW/liter. These particle temperatures required a significant advancement over the capabilities of the nuclear particle fuels developed for the High-Temperature Gas-Cooled Reactors (HTGR) and developed during the NERVA/ROVER NTR program: the maximum fuel temperature demonstrated in a nuclear environment during the NERVA/ROVER program was in the range of 2400-2600 K, but they projected temperature capabilities of over 3000 K. The approach of the Fuel Development effort was first to produce a particle based upon the design developed in the HTGR program, this particle design was labeled the "baseline" fuel particle. The second thrust of the effort was to develop an advanced fuel particle capable of supporting the performance goals of the SNTP Program.

The program team's ability to produce the baseline fuel particle was initiated in 1987 with the transfer of the technology and the equipment to manufacture coated microparticle fuel from Oak Ridge National Laboratory (ORNL) to B&W. This transfer included the ability to produce uranium-bearing ceramic kernels via the internal-gelation process with a pyrocarbon coating using a chemical vapor deposition (CVD) utilizing a fluidized bed technique. B&W developed their own ability to produce a ZrC outer coating on the microparticle with the aid of Los Alamos National Laboratory and General Atomics. B&W produced fuel particles in support of the PIPE experiments carried out in 1988 and 1989.

The SNTP baseline fuel particle design is based upon the particles B&W produced for the PIPE experiments. These particles, Fig. 4.5-1, consist of a UC_{2-x} kernel: the exact composition varies with manufacturing conditions. The fuel kernels are coated with two layers of pyrocarbons and a outer layer of ZrC. The first pyrocarbon layer is a porus layer that accommodates the mismatch in the thermal coefficient of expansion between the kernel and the outer ZrC coating. The second pyrocarbon is a dense layer necessary to protect the kernel from chemical attack by the halides used in the ZrC CVD coating process. Finally, the outer ZrC layer is necessary to protect, or more accurately delay, the chemical interaction between the carbon and the hydrogen propellant.

Baseline fuel particles were manufactured, tested in a series of Particle Nuclear Tests (PNT) and Particle Heating Tests (PHT), and used both in the CX and the Nuclear Element

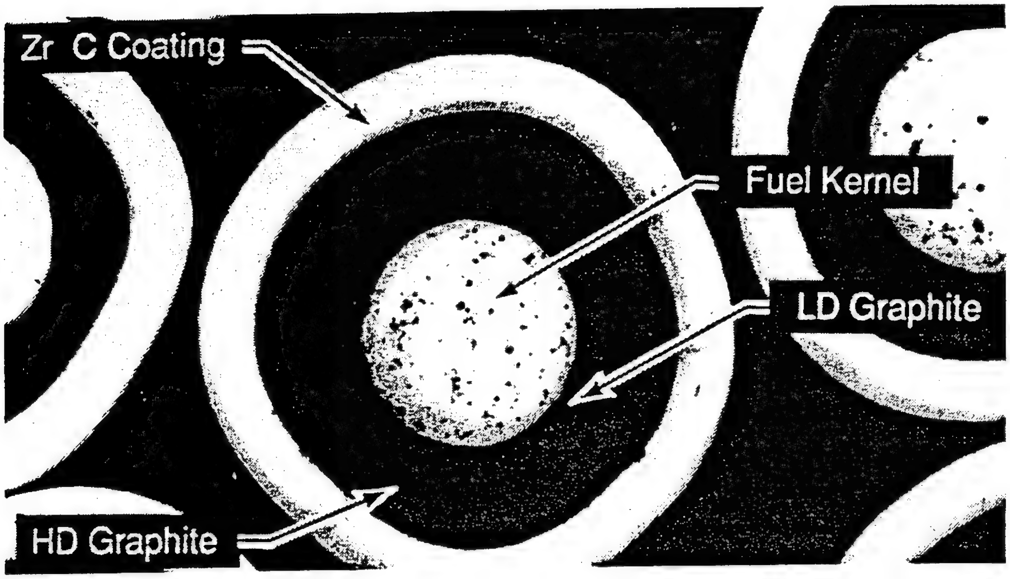


Figure 4.5-1 A baseline fuel particle: UC_{2-x} kernel, pyrocarbon layers, with an outer coating of ZrC or NbC. The particle is ~0.5 mm in diameter.

Tests (NET). By the end of the program the following tests utilizing baseline fuel particles were successfully completed: (1) numerous PHT's using furnances at B&W's laboratory facilities, (2) PNT 1 through 5a in Sandia's Annular Core Research Reactor (ACRR), (3) the NET-1.2 campaign in the ACRR, and (4) numerous tests in CX to determine reactor physics parameters. Just in PNT 1-4 over 200,000 particles were tested in a nuclear environment at temperatures ranging from 1800-3000 K and for times from 100 to 600 seconds.

The baseline fuel particle is theoretically limited to maximum operating temperatures dictated by the melting point of the UC_{2-x} kernel, between 2700 and 2800 K, and operating with a molten core is not possible. Figure 4.5-2 is the phase diagram for uranium and carbon. PNT-3 and PNT-4, performed at Sandia National Laboratory, tested baseline particles to failure. These tests indicated that the actual operating temperature limit of the baseline particle is approximately 2500 K. Once the UC_{2-x} kernel becomes molten, it dissolves the two buffer layers of carbon and then attacks the ZrC outer layer. Once the kernel becomes molten the failure of the outer coating occurs in approximately five minutes. During the 1991-1992 time frame the program discussed the production of an advanced baseline particle to support testing, but not for use in a SNTP system. The thickness of the buffer carbon layers on the UC_{2-x} kernel would have been increased to delay the time to particle failure. Due to funding constraints with resulting delays in the testing schedule and the promise of advance particle concepts, the program decided not to produce and use an advanced baseline particle.

The limitation of the baseline particle was anticipated early in the program, but a fuel particle was needed to support other WBS elements and to conveniently acquire an experience base. Knowing that the baseline fuel particle could not support the program's ultimate goals, the SNTP program undertook the development of an advanced fuel particle and a dual-path of development was pursued to minimize the risk. BNL pursued the development of an infiltrated kernel (IK) particle and B&W a mixed-carbide particle.

The IK-particle was based upon the high melting point of graphite and the assumption that UC_2 is thermodynamically stable with respect to graphite and will not react with it even

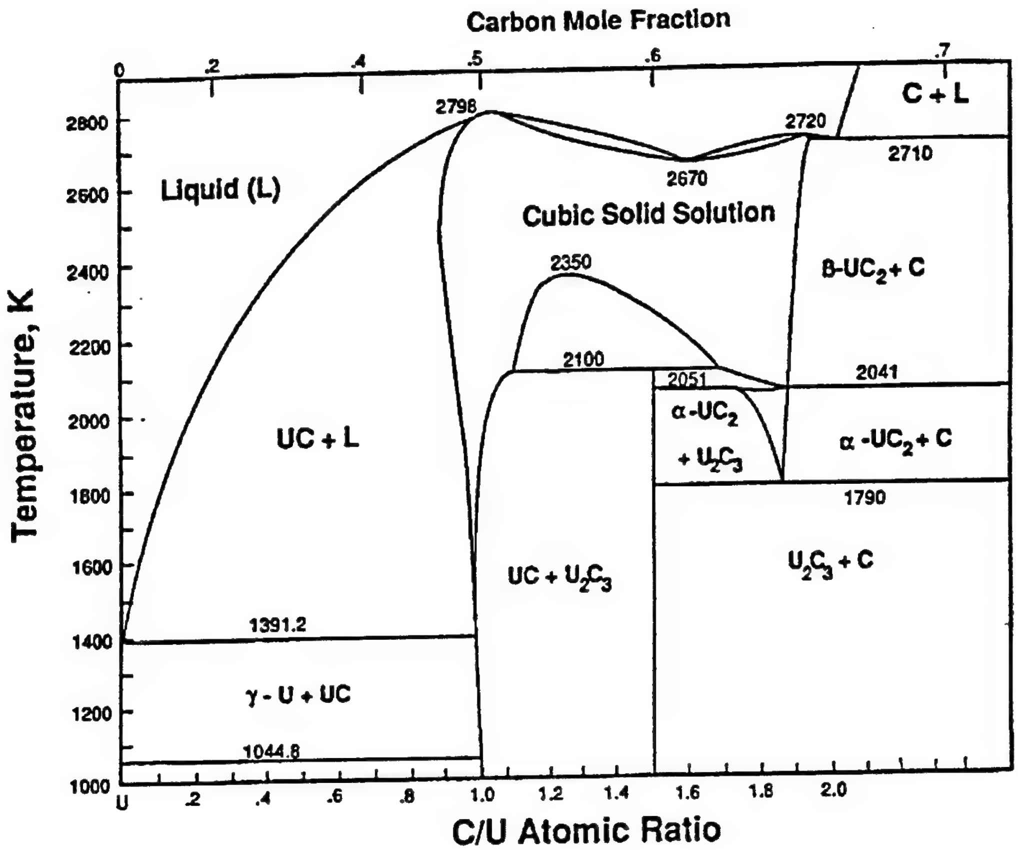


Figure 4.5-2 The phase diagram for uranium and carbon.

at temperatures in excess of its melting point of 2720 K. Based upon these premises, BNL scientists postulated that molten UC_2 would distribute itself uniformly throughout a porous graphite matrix and could be stably held inside the graphite pores. The infiltrated kernel would then be coated directly by an appropriate metal carbide to protect it from the hydrogen propellant. Because of the porosity of the kernel and the manner in which the UC_2 was held in the graphite matrix the protective pyrocarbon coatings necessary in the baseline design are not necessary in the IK design; thus, allowing for a higher uranium particle density, a smaller particle bed, and a more compact system. The first necessary steps in the development of an IK particle were to develop a process that would infiltrate the UC_2 into the graphite matrix to the required densities and to develop a process for manufacturing porous graphite microspheres. By the end of 1992 BNL had demonstrated, on a laboratory scale, that they could infiltrate UC_2 into graphite coupons to the desired density and manufacture graphite spheres.

The interest in a mixed-carbide nuclear fuel dates to the end of the NERVA/ROVER program when its was investigated in an attempt to reduce midband corrosion. Mixed-carbide fuel is a mixture of refractory carbides, such as, ZrC, NbC, TaC, and HfC, and UC. The refractory carbides have melting points ranging from 3700 K for ZrC to greater than 4200 K for HfC and TaC: UC has a melting point of 2798 K. Due to the high neutron absorption cross-section of Ta and Hf only the ternary mixtures of U-Zr-C and U-Nb-C have been considered. Figure 4.5-3 is a phase diagram for UC-$ZrC_{0.81}$, as an example of a mixed-carbon fuel

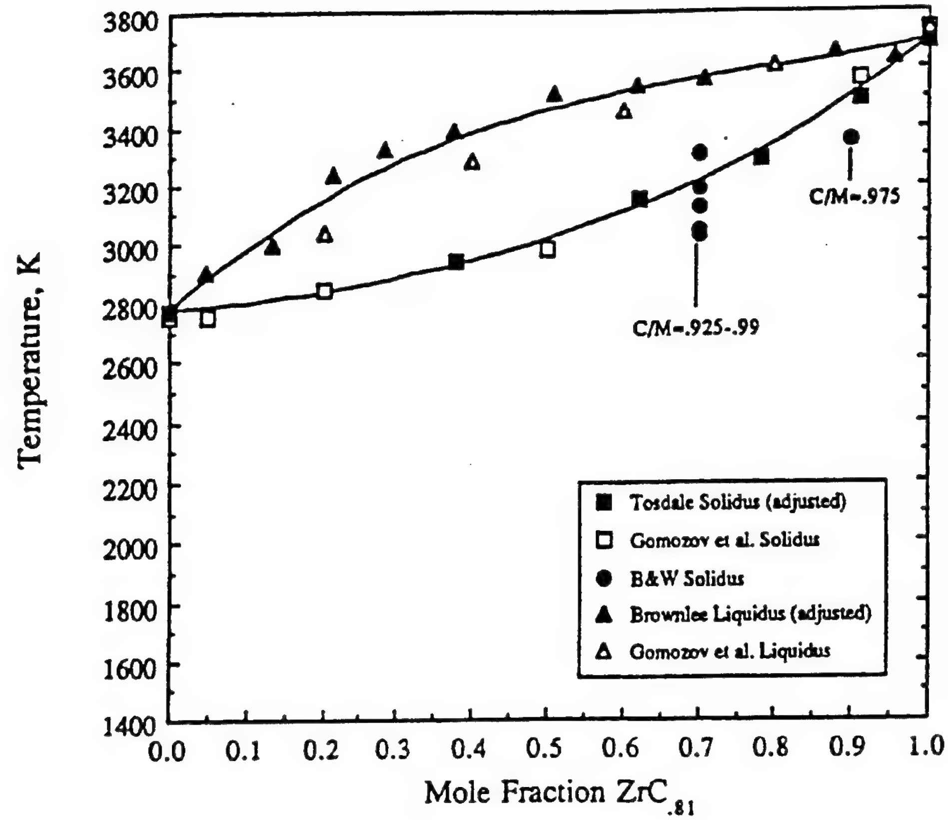


Figure 4.5-3 The UC-$ZrC_{0.81}$ pseudobinary (ternary) phase diagram (from D. P. Butt and T. C. Wallace, "The U-Zr-C Ternary Phase Diagram Above 2473 K," accepted for publication in the J. Am. Cer. Soc., 1993)

composition. The melting point of these systems decline as the uranium content is increased; however, the minimum uranium content is dictated by criticality issues at an approximate mole fraction of 0.15, which translate to melting temperatures of approximately 3200 K. As in the other particle designs, it was anticapated that the mixed-carbide particles would require a refractory carbide coating to retard the chemical interaction with hydrogen to increase the particle's lifetime.

Even though the program had committed to two equal paths of advanced fuel development, the reality of the funding did not allow the extensive development of the mixed-carbide fuel. However, by the end of 1992 B&W did determine the melt point of the U-Zr-C as a function of composition, measure the plastic deformation of ZrC, NbC, and U-Zr-C compositions at 3200 K, and produce a small quantity of NbC coated U-Zr-C kernels using internal-gelation process with the CVD coating technique.

By the end of 1992 the SNTP fuel development effort had come to a critical decision point. Due to funding and programmatic reasons, the fuel development team was asked to make a choice of the preferred advanced fuel; however, the fuel development team was split and was unable to come to a consensus. Two events had a strong influence on the path the fuel development effort appeared to be taking when work effectively stopped in the spring of 1993. In 1992 rumors started to circulate in the community that in support of the former Soviet Union's Nuclear Rocket Engine (NRE) Program, Russian scientists had developed and tested mixed-carbide fuel capable of 3500 K and that they produced not only the ternary fuels, U-Zr-

C and U-Nb-C, but also a quaternary fuel, U-Zr-Nb-C. In September of 1992 SNTP representatives met with representatives from the Russian institute, NPO Lutch, the institute responsible for the development, testing, and manufacturing of the mixed-carbide fuel, in the U.S. and then again while attending the Third Specialist Conference, Nuclear Power Engineering in Space Nuclear Rocket Engines in Semipalatinsk, Kazakhstan. Based upon these contacts the SNTP Program office at Phillips Laboratory supported a Grumman effort to enter into a contractual agreement with Lutch for support of the program in the areas of nuclear fuel, advanced high-temperature materials, and testing.

The Grumman-Lutch contract was reviewed and agreed upon by the Russian government. The Statement of Work, approved by the Program Office, defined five tasks:

- Task 1 - manufacture and supply mixed-carbide particles, both coated and uncoated of natural and enriched uranium, for charaterization and testing in the U.S.

- Task 2 - the supply of data for the release of fission products from mixed-carbide nuclear fuel at elevated temperatures and its subsequent deposition from a hydrogen effluent stream. This task also called for the joint U.S.-Russian development of empiricial correlations for the release and deposition of the fission products.

- Task 3 - the supply of thermal-mechanical data and samples for testing in the U.S. of high-temperature refractory materials, porous refractory materials, and refractory coatings.

- Task 4 - an evaluation of nuclear rocket test facilities in the former Soviet Union that may have been utilized by the SNTP Program.

- Task 5 - technical planning and coordination for the contract.

The second event that influenced the planned fuel development path of the SNTP Program was the formation, at the direction of the program office, of a national panel of high-temperature nuclear fuel experts to evaluate the various fuel alternatives. The panel consisted of experts from within and external to the SNTP Program. The experts represented both industry and a number of national laboratories. This panel reviewed reports and presentations by BNL on the IK-particle development and B&W on the mixed-carbide fuel development efforts. It also considered reports and presentations from Phillips Laboratory, Edwards AFB on an alternative infiltration process for the IK particle; from Los Alamos National Laboratory on the knowledge status of mixed-carbide fuels; and from Grumman on the known status of the Russian mixed-carbide fuel. The expert panel provided the following statement in their comprehensive recommedation to the SNTP Program Office:

"... the Fuel Evaluation Panel recommends that the SNTP Program's Advanced Fuel Development concentrate its effort and funding on the development and production of mixed-carbide nuclear fuels, specifically, the $(U_xZr_{1-x})C$ and the $(U_xNb_yZr_{1-x-y})C$ systems of mixed uranium, refractory metal carbide solid solution, possibly coated with NbC, TaC, or a co-deposition of these materials."

When work on the SNTP program stopped the fuel development effort had a focused

approach that would have resulted in a significant leap in the technology of high-temperature nuclear fuel:

- The Grumman-Lutch contract would have enabled the U.S. to capture the benefit of the Russian's multi-year mixed-carbide nuclear fuel development effort. Due to termination of the program the contract was never consummated and the opportunity to capture this technology appears to be lost.

- Los Alamos was poised to become an associate contractor to the program and bring their world-wide recognized expertise and world-class facilities to the fuel development effort.

The opinion among the fuel development team was that within two years and relatively modest funding the SNTP fuel development effort would have resulted in the characterization of mixed-carbide fuel, the development of the processes to manufacture the fuel, and the production of fuel necessary to support its testing in a nuclear environment, NET's, and reactor tests in PIPET.

4.5.2 Accomplishments

A list of accomplishments of the fuel development effort, starting in 1987, as described above in the overview include:

- The acquisition of the technology and equipment, via a tech transfer from ORNL, to produce nuclear fuel microparticles using the internal gelation process and coat the particles, with both pyrocarbon layers and refractory-metal carbide layers, using the CVD process.

- The production of baseline fuel particles to support the PIPE's, the PNT's, the PHT's, the CX, and the NET's.

- The development of a laboratory process to infiltrate porous graphite with uranium to densities in the 1-2 gm/cm^3 range.

- The development of a laboratory process to make spherical microparticles of graphite.

- The modification of the internal-gelation process to produce U-Zr-C particles.

- An agreement with NPO Lutch, with approval by the Russian government, for the delivery and testing of mixed-carbide particle fuel of both ternary and quaternary compositions.

- A review of a nationally recognized panel of experts and their recommendation to pursue the development of mixed-carbide fuel.

4.6 WBS 1.6 Fuel Element

4.6.1 Overview

The basic building block of the Particle Bed Reactor is the fuel element, and its development was a major R&D effort in the program. The fuel element development was supported by one of the program's primary test series, the Nuclear Element Tests (NET). The NET program planned to not only validate the fuel element but also to provide particle fuel design, and other data. The test would have included above-design conditions and characterization of failure modes, served to validate new instrumentation and control concepts, and validated design codes.

The fuel element consists of the hot and cold frits used to contain the nuclear particle fuel and control radial flow of hydrogen over the fuel bed, the moderator used to slow (or moderate) neutrons, and other hardware elements and features needed to assure proper cooling, structural integrity and stable control of the reactor. The nuclear, thermal, hydraulics, mechanical and structural design and performance requirements derived from the high temperature, high power density, high I_{sp} and thrust-to-weight requirements for the engine system made this a complex subassembly whose successful development directly impacts the overall success of the PBR.

The plan was to design, fabricate and test a series of fuel element systems that would be subjected to increasing levels of performance demands during nuclear tests in the SNL ACRR. The program had just reached the first nuclear NET when a program slowdown occurred, with a program termination pending. The Program Office authorized additional funding to perform and complete the testing of the first NET fuel element, which was accomplished.

4.6.2 Accomplishments

- Completed the first Nuclear Element Test (NET 1.2) and performed post irradiation examination (PIE)

- A fuel element was designed, fabricated, analyzed and tested in a near prototypic environment
  - Flowing hydrogen at cryogenic temperatures
  - Nuclear heating by prototypic fuel particles

- Conceived, designed, fabricated, and analyzed a complex experiment (NET) to test fuel elements in flowing hydrogen in Sandia's ACRR.
  - Integrated experiment team, personnel from the Air Force, Grumman, Babcock & Wilcox, Sandia, and Brookhaven National Laboratories
  - Realtime, hardware-in-the-loop, experiment simulation
  - Computer based flow control system

- Developed several complex computer programs to analyze flow distribution within the fuel element and the NET capsule. (see Section 4.9)

- Undertook considerable analytic and modeling effort to better understand potential flow instabilities. The causes and regions of possible flow maldistribution were defined.

4.6.3 Cold Frit Design

The cold frit is the outer tapered circular cylinder enclosing the fuel particles. This device is required to distribute flow axially and circumferentially around the outside of the fuel bed. It must meter the flow so as to match the power distribution within the fuel bed. This is known as flow to power matching, and requires significant analytic effort to determine the required flow distribution. Considerable time and effort was also required to develop a mechanical design that could produce the required flow distribution.

The cold frit is also required to absorb the thermal expansion of the fuel bed as well as returning the bed to its original position during cool down. The bed must return to its original position to prevent "ratcheting", progressive radial growth of the fuel bed with each thermal cycle. Ratcheting would impose unacceptable loads on both the fuel particles and the hot and cold frits.

The first cold frit designed was porous sintered aluminum. Flow distribution was controlled by micropeening the outside surface of the frit. Bed expansion was intended to radially expand the frit within its elastic limit. This design was tested under the DOE's Multimegawatt program and found to be inadequate. Details about this test, known as PIPE, are at Sandia National Laboratory.

The porous sintered aluminum frit had two major problems. First, the micropeening closed many of the tiny flow passages and made the remaining ones very susceptible to plugging. Second, bed expansion placed unacceptable loads on the fuel particles and the cold frit itself. Subsequent analysis also suggested that the heating of the cold frit by the fuel particles, called "back conduction",could contribute to flow instability, especially at low flow conditions.

The approach taken to providing flow control that would be resistant to plugging and insensitive to bed temperature was to utilize the platelet technology developed by Aerojet for controlling flow in liquid rocket engines. A multi-cellular platelet stack was designed that has screening as the outer layer protecting the metering layer from plugging. There were ten cells circumferentially and twelve cells axially for a total of 120 cells in the cold frit. Each cell had twelve metering holes to control flow quantity followed by distribution layers to blend the flow from the individual holes. The distribution layers also positioned the metering layer away from the fuel bed thereby reducing the effects of back conduction.

To accommodate bed expansion a compliant layer was developed consisting of a thin A286 stainless steel screen bonded to a grid that matches the 120 flow cells of the metering and distribution layers. Bed expansion would be accommodated by deflection of the screen into the space behind it. The metering layer assembly and the compliant layer were each formed into a half cylinder and then bonded to each other. Two of these assemblies were then welded together to form the cold frit. The compliant layer also provides additional insulation from bed heating for the metering layer.

During the design and development process of the platelet cold frit, mission analysis and engine design efforts found that considerable engine propellant could be saved if the cold frit were allowed to increase in temperature, from decay heat, during the cooldown between engine starts. This was accomplished by changing the design of the platelet stack to 304L stainless steel.

4.6.4 Hot Frit Design

The extreme high temperature, flowing hydrogen environment that the hot frit is required to endure, severely restricts the choice of materials that can be considered for the hot frit. Two kinds of hot frits were fabricated, ZXF-5QI graphite and carbon-carbon. Both were coated with niobium carbide to help prevent the H_2 from reacting with the carbon in the frit. The flow passages were provided by 55,211 mechanically drilled holes. The NbC coating was judged more likely to be contiguous on the smooth graphite surface than the woven texture of the C-C surface; ergo the graphite hot frit was used in the NET-1.2 test.

As discussed in more detail in Section 4.6.6, the hot frit failed in the NET-1.2 test. World events occurring in parallel with the hot frit development and testing have indicated that there may be other materials now available for consideration in hot frit design. The Former Soviet Union has reported that they have done extensive research and development in the manufacture of carbide metals. It was planned to obtain samples of carbide metals from NPO Lutch to make and test monolithic niobium carbide or zirconium carbide hot frits.

4.6.5 Nuclear Element Tests (NET)

A series of NET experiments were planned in support of SNTP Fuel Element Development. These experiments would have provided engineering data to address the key issues for developing PBR fuel elements:

- Adequately match flow to power.
- Accommodate differential thermal expansion within the element.
- Thermally isolate structural components from the high temperature exhaust gas.
- High temperature component ability to withstand severe thermo-chemical environment.
- Provide these capabilities over a number of operating cycles,

NET-1.2 was the first of four planned element tests and was the only test completed. It was conducted in the ACRR to provide prototypic internal (fission) heating of the particle fuel in a representative element configuration. The specific parameters identified to be investigated by the first four experiments are contained in the NET Requirements Document (Ref 4.6-2) and are summarized in Figure 4.6-1.

The experimental capability exists to achieve element design operating temperatures using the ACRR as a source of neutrons to fission heat representative elements while actively cooling the element with hydrogen. These experiments would have provided data early in the

Test Condition	NET-1	NET-2	NET-3	NET-4
Maximum Hydrogen Outlet Temp, K	2300	2500	3000	>3000
Hydrogen Inlet Temperature, K	150	150	150	150
Specific Power, MW/L	1.5	5	5	5
Fuel Bed Length, cm	25	10.6	10.6	10.6
Cold Frit Material	SS	SS	SS	SS
Hot Frit Material	Graphite/NbC	Graphite/TaC	Graphite/TaC	Graphite/TaC
Fuel Type	UC2/ZrC	UC21NbC	Advanced	Advanced
Cycles to maximum temperature	2	2	30-50	
Nominal U235 Mass, g	400	125	TBD	TBD
Nominal Fuel Volume, cc	300	140	140	140

Figure 4.6-1 NET Experiment Parameters

SNTP Program to evaluate the performance of the element, including flow stability through the element. They were also to help validate the design parameters and analytical models necessary to design and safely operate nuclear fuel elements and nuclear reactors intended to be used in future SNTP reactor systems. Fuels and fuel element testing, such as NET, would be required for licensing and operating nuclear reactors planned to be developed by the programs. A section of the NET Experiment capsule is shown in Figure 4.6-2

NET-1.2 Objectives

Objectives of the NET series of experiments were to provide engineering data to help validate and demonstrate critical fuel element related technologies and provide an experimental data base to support analytical design methods for the SNTP Program. These tests were planned to support design and development of fuels and the fuel elements as well as safety evaluations and characterization of operating limitations for future space reactor systems. The testing of these fuel elements was a necessary step in establishing the feasibility of Particle Bed Reactor (PBR) technology to meet the performance goals to support the SNTP program, and NET testing emphasized early demonstration of key technologies with performance evolution to support the development of particle bed nuclear reactors.

Specific objectives of the first experiment were:

- Provide engineering data to evaluate the performance of a particle bed fuel element
- Demonstrate the ability to operate at target temperature while retaining the ability to cycle the fuel element
- Evaluate flow to power matching

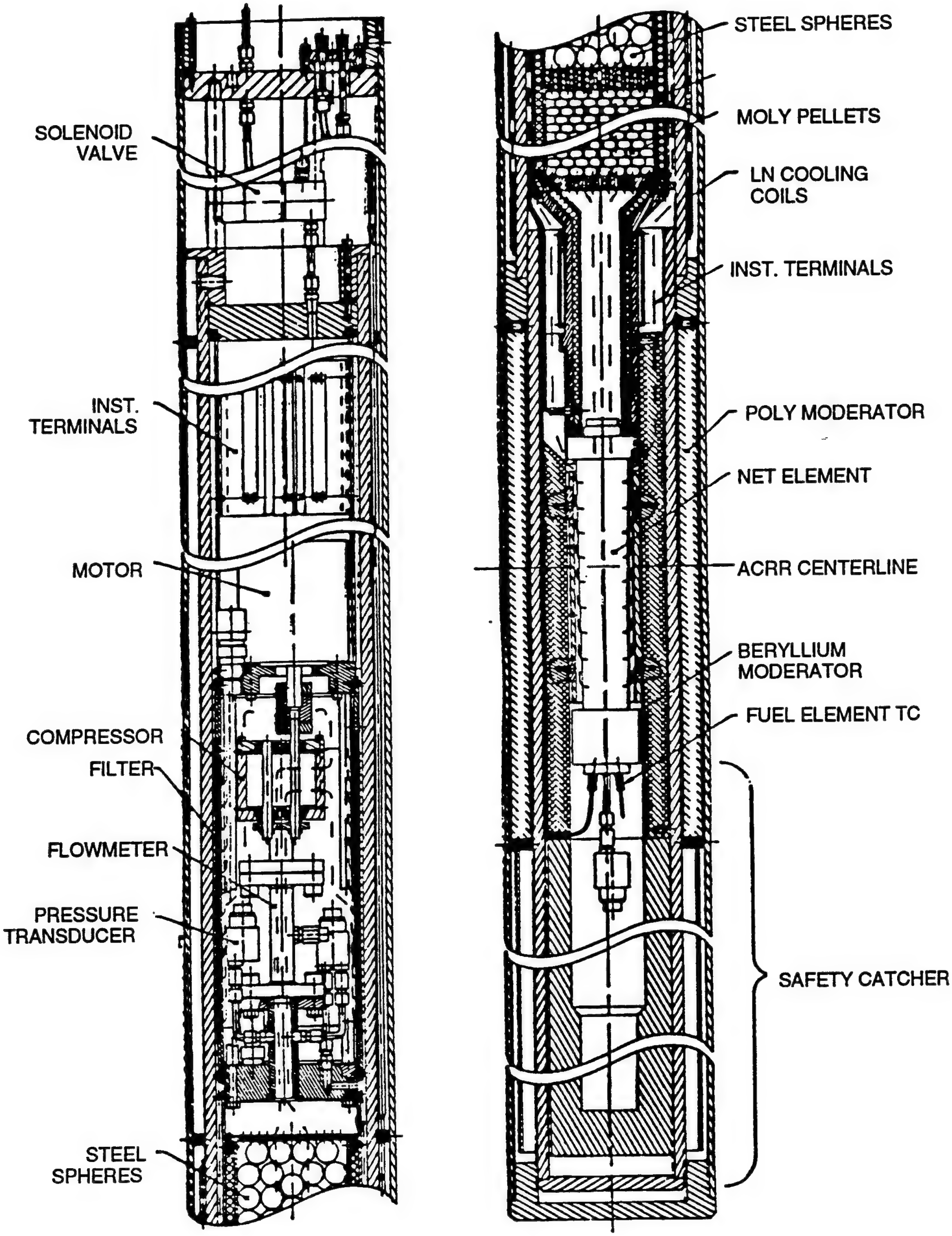


FIgure 4.6-2 NET Experiment Capsule

- Provide data to assist in the evaluation of flow stability
- Provide data to assist benchmarking thermal-hydraulic models

To accomplish these objectives, numerous test runs at various powers and cooling flow rates were to be accomplished in the ACRR, as described in Ref. 4.6-1. These runs incrementally accomplish the identified objectives by providing data as the experiment proceeds, allowing the progression of the experiment from relatively benign conditions to operations which stress the element design. In addition to data obtained by recording physical parameters during experiment operation, information regarding performance of the fuel element was obtained by post test examination of the element.

NET-1.2 Experiment Description

NET experiments were identified sequentially by test number and fuel element. NET-1.2 was the first SNTP test of a particle bed fuel element, using the second (NET-1.2) element designed and fabricated by the program.

The NET-1.2 experiment assembly was designed to actively cool a fission heated nuclear fuel element with hydrogen. A coolant inlet temperature as low as 150 K was achieved by precooling portions of the experiment capsule with liquid nitrogen. The experiment assembly is designed to position the NET-1.2 fuel element at the centerline of the ACRR neutron flux, and polyethylene and beryllium moderators were incorporated into the capsule design to maximize the fission energy deposition in the fuel. The fuel element and flow control components were contained within a hydrogen pressure vessel, which was further contained within a radiological containment barrier. Large thermal masses were included as safety features in the unlikely event of melting of the fuel element. They were designed to absorb the maximum fuel element energy deposition and protect the hydrogen pressure vessel and containment in an accident scenario.

Fuel element and hydrogen temperatures were measured during the experiment and the coolant flow rate maintained by a computer based flow controller to achieve various target temperatures at several different power levels.

Fuel Element Summary Description

The NET 1.2 experiment tested the second fuel element designed and fabricated by the SNTP program. This was a fuel element which was representative of flight or ground test elements in its design features and materials but had a fuel bed length of approximately 25 cm (approximately 60% of full length). The element utilized the baseline ZrC coated fuel particles and a NbC coated graphite hot frit. It had a stainless steel platelet cold frit which contained provisions for the accommodation of fuel bed thermal expansion. The cold frit also had the critical function of properly distributing the inlet flow to the fuel bed, which was accomplished by a metering layer within the platelet stack and by subdividing the frit into cells to prevent the axial and circumferential redistribution of flow within the frit. The element design differed from that for use in a ground test or flight engine in that the assembly was bolted together instead of being completely welded. This facilitated disassembly during post irradiation examination (PIE).

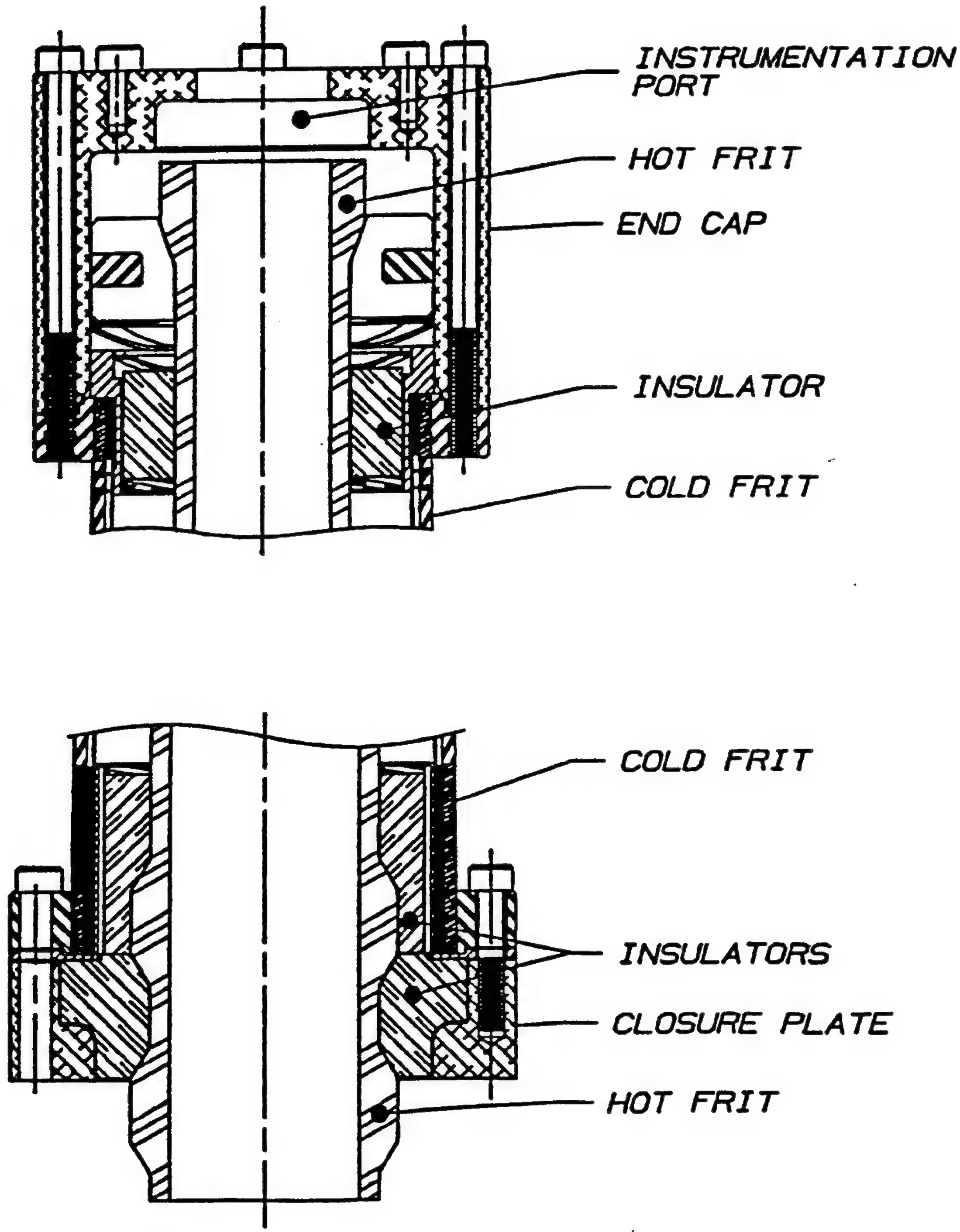


Figure 4.6-3 NET-1.2 Fuel Element

Figure 4.6-3 shows both of the element end fittings and illustrates the major components within the fuel element. Instrumentation included in the fuel element consisted of:

- Displacement transducers
- Cold frit structure thermocouples
- Cold frit inner layer temperature thermocouples
- Cold frit gas temperature thermocouples
- Flange temperature thermocouples
- Hot channel gas temperature thermocouples
- Differential pressure transducers

A complete description of the fuel element is contained in the NET-2 Fuel Element Design Document (Ref 4.6-3). A comprehensive design review of the NET-2 element was completed by B&W on October 22, 1992.

4.6.6 NET 1.2 Test Results

The initial test runs were completed satisfactorily with the expected amount of instrumentation and control problems inherent in a complex new experiment. On the second run to moderate temperature (≈1700 K) ACRR power irregularities halted testing. It was concluded and (later verified by an x-radiograph) that the ACRR power anomalies were indicative of potential fuel movement within the NET 1.2 fuel element. The Program Office then authorized SNL & B&W to perform a minimal post irradiation examination (PIE), which confirmed the existence of circumferential breaks in the hot frit.

The NET-1.2 PIE activities occurred during the months of November and December 1993 in the Hot Cell Facility (HCF) at Sandia. Ultimately, five cracks were found on the hot frit; two complete circumferential fractures (through the thickness), both in the active flow region about 3/8 inch in from each end, one longitudinal fracture (also through thickness) that extended from the closed end circumferential crack about 4 inches upward along the frit wall, one small partial through-wall circumferential fracture which was very close to the termination of the main longitudinal crack, and one fracture that extended beyond the flow region of the lower part of the frit near the closed end.

Initial optical inspections of the failures indicated several important points. First, the presence of fuel particles in the through-thickness axial crack suggested that this failure was caused by unexpectedly large hoop stresses in the frit wall. The most likely explanation is that this occurred after the two circumferential breaks formed, when a significant amount of fuel had relocated into the central channel. Post-test analyses using a relocated fuel bed were consistent with this theory indicating stresses which exceeded failure levels by significant amounts.

Secondly, the apparent uniform appearance and almost symmetrical location of the two major circumferential breaks suggested that these failures were the result of excess thermal stress placed on the hot frit wall. Post-test analyses indicated that the general location of the failures was consistent with regions of peak stresses (i.e., near the hot frit/end fitting interfaces).

The causes of the two small cracks are unknown at this time although both are believed to be artifacts of the initial failures which allowed the fuel relocation. The through-wall crack extending downwards from the lower circumferential fracture to the bottom of the frit was probably caused by differential thermal expansion created when fuel particles became trapped between the stainless-steel thermocouple plug and the hot frit wall.

The cold frit was also studied. It was observed that practically all of the cold frit compliant panels were deformed close to or at their maximum predicted operational deformation. The shape of the panels was roughly parabolic. This shape suggests that the fuel bed was never fully "locked" between the hot and cold frits and therefore reduces the probability that hot frit failure was due to loading from the bed.

4.6.7 Summary & Conclusions

Significant progress was made in fuel element design and analysis by the SNTP program. All testing and analysis confirmed that the basic PBR concept is sound. No fundamental problems were encountered and a much greater understanding of and experimental techniques for dealing with flow instability were developed.

The problems which led to the failure of the hot frit are not thought to be inherent design limitations or physical limitations on the performance of the materials chosen. All of the failures, including the anomalous cold frit compliant panel deformations, can be easily corrected through fairly simple redesign strategies and improved pre-test response analyses. Based on the appearance and the resulting postulation regarding the permanent deformations of the compliant panels, it is felt that the cantilever panel design approach, already developed by B&W, would significantly improve the performance of the layer. Additionally, improved analysis of the thermal response of the hot frit/end fitting interfaces would allow better prediction of the actual thermal gradients that the hot frit must withstand. This information, along with improved coating methods and pre-test component inspections, would allow the fabrication of new frits (using the same materials) that could withstand the conditions imposed by the NET-1.2 test matrix. In addition it was planned to investigate the use of metal carbides developed in the former Soviet Union to make the hot frit design more robust.

4.6.8 References

4.6-1 NET-1.2 Final Test Plan, April 30, 1993 G.W. Mitchell et. al.

4.6-2 NET Requirements Document, LV-S-14-225-92, 8/1/92

4.6-3 NET-2 Fuel Element Design Document, Babcock & Wilcox Document 51-3001941-00, October 1992

4.6-4 NET-1.2 Post-Irradiation Examination Report, February 1994 by M. Rightley, M.Ales & S.Bourcier

4.6-5 SNTP Program NET 1.2 Summary Report, SNL Document SAND-94-2229 (in review)

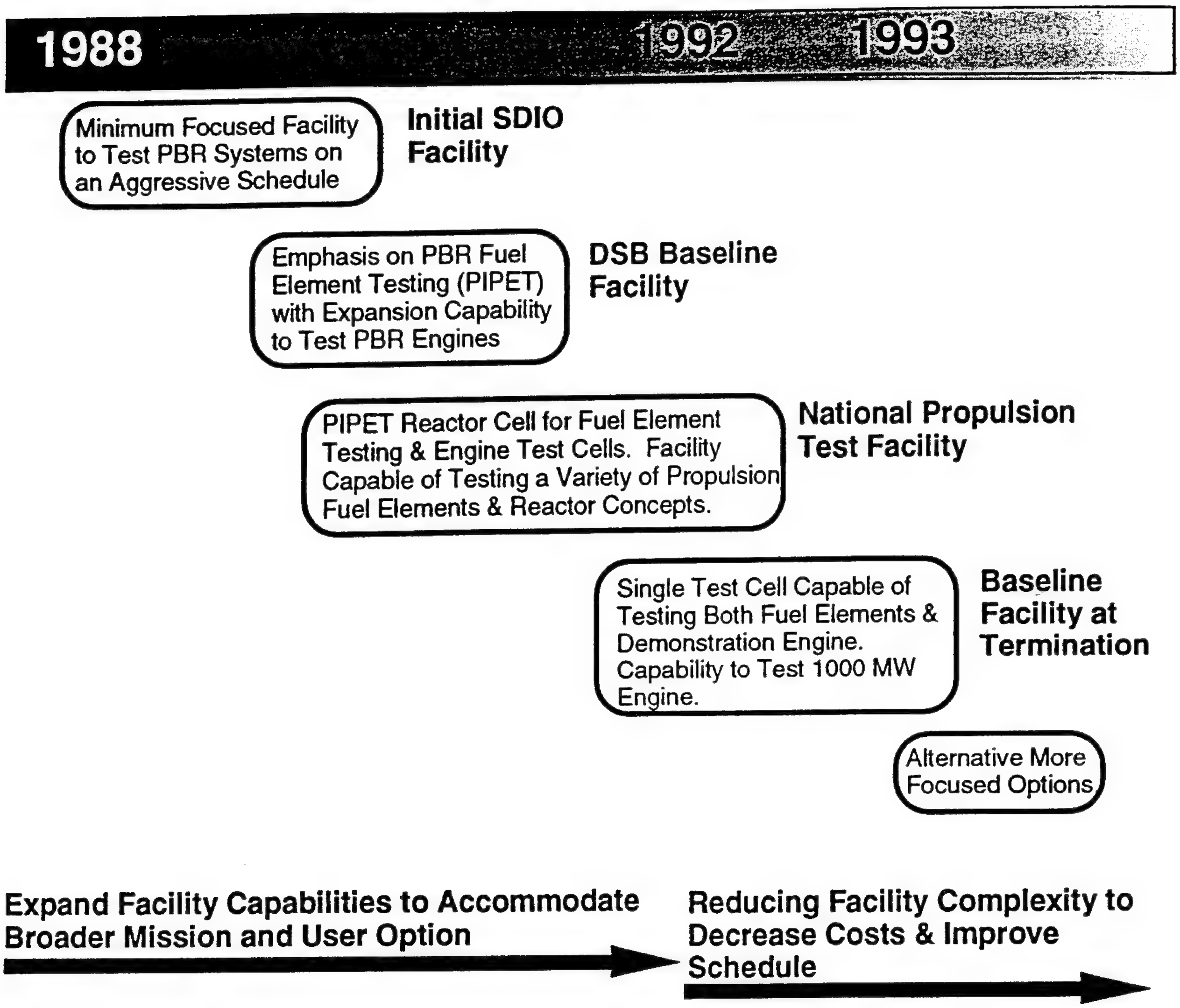


Figure 4.7-1 Timeline for the Ground Test Facility

4.7 WBS 1.7 PIPET

4.7.1 Introduction

PIPET was the planned test reactor that was to be built to address the technology issues associated with the development of a PBR-based NTP engine. PIPET stood for the Particle-Bed Reactor Integral Performance Element Tester. Originally, PIPET was the fuel element test reactor, but often the acronym was used in reference to the entire facility or test project. As the planned test facility's scope changed the acronym became inappropriate, but the name remained. Figure 4.7-1 depicts the evolution and planned future of the SNTP nuclear ground test facility.

Initially, PIPET was envisioned as a relatively small and low-cost test facility to provide the operating environment necessary to adequately test PBR-reactor fuel elements for the SNTP program. Over time and out of necessity dictated by regulatory requirements, and

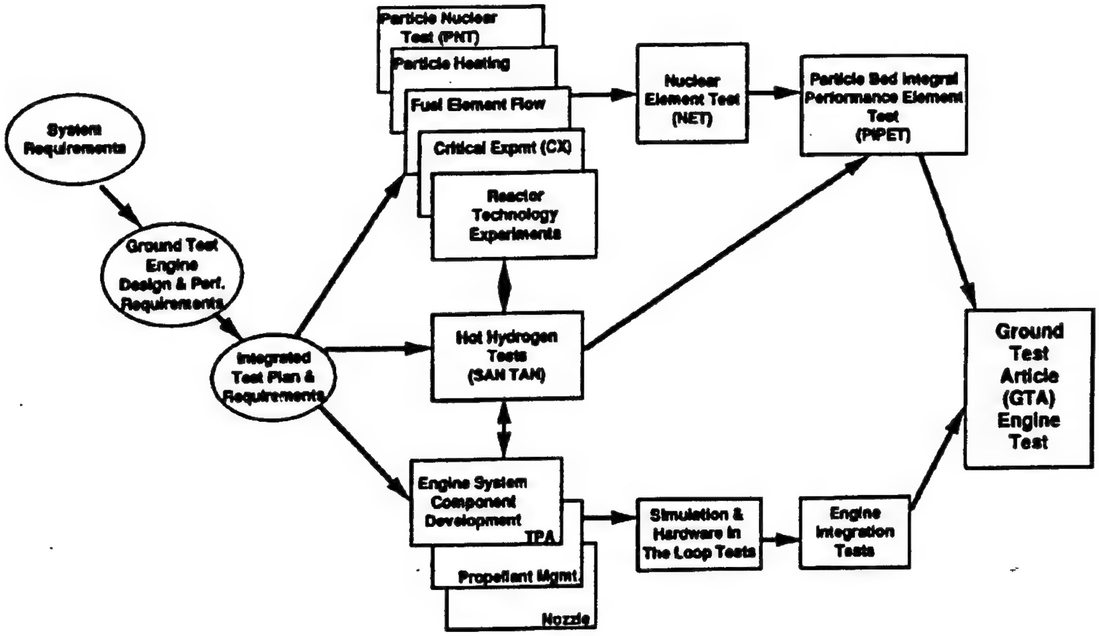


Figure 4.7-2 SNTP Test Plan Flow Chart

government and program demands PIPET evolved into the fuel element test reactor of an elaborate SNTP nuclear ground test facility which also included a separate facility for testing integrated NTP engines: this facility was viewed as a national resource for testing a wide range of NTP concepts. Over the last eighteen months of the program there was a concerted effort to reconfigure the facility to one that was less costly and still flexible enough to meet the demands of a national ground test facility for different NTP concepts. This last metamorphosis consisted of a single test cell that could be used for fuel element tests, reactor core tests, and integrated engine tests. By the end of the program PIPET referred to this flexible, multipurpose test facility and no longer was just a reactor for testing PBR fuel elements.

4.7.2 PIPET's Role in the Program's Test Program

PIPET was an integral part of a success oriented, building-block approach to ground test and qualifying an integrated SNTP engine with as little risk and in as short a time as possible. Figure 4.7-2 shows the SNTP test plan, highlighting PIPET's role in reference to the program's other tests. The program's test plan consisted of two basic branches: a nuclear systems branch and non-nuclear systems branch. The main propose of the nuclear test branch was to systematically test and qualify the nuclear reactor for the SNTP engine. This step-wise approach started with the Particle Nuclear Tests (PNT) (Sec. 4.5), then the Nuclear Element Tests (NET) (Sec. 4.6), and finally the testing of integrated elements in a critical assembly. The non-nuclear test plan was to test and qualify the propellant management system, the nozzle, and the other engine system components. The non-nuclear components would first be tested in a simulation and hardware in the loop test (Sec. 4.9) and then in the Engine Integrated Tests (Sec.4.8). PIPET was an important part of the nuclear branch, but as a multipurpose test bed it also was the culmination of both branches of the test plan in the ground test demonstration of an SNTP engine. Its three major roles were to: (1) qualify the nuclear fuel and fuel element at prototypical conditions, (2) qualify the reactor core at

prototypical conditions, and (3) test a Ground Test Engine (GTE).

To qualify the nuclear fuel, fuel element, reactor core, and GTE the Program required a facility that would not only demonstrate that each of these items could operate safely in its specified realm, but also needed to be able to show a reasonable margin of safety in the event of an upset. The nominal operating specifications for the SNTP engine were a hydrogen mean-exit temperature of 3000 K, an average particle bed power density of 40 MW/liter, with an operating time of 1000 seconds. A test reactor was not available nationally or internationally that could duplicate the specified operating conditions, let alone provide the assurance of a reasonable safety margin. The NERVA/ROVER test facilities at the Nevada Test Site are still partially intact; however, the facilities were over twenty years old by late 1980's when they were evaluated and were not designed or built to meet present requirements. In support of the Program's NEPA process, the NTP subpanel of the Interagency Space Propulsion Test Facilities Panel recommended that prototypic fuel/fuel element and reactor/engine test facilities needed to be newly constructed. Figure 4.7-3 compares the capabilities of different reactors to the SNTP tests and goals. As this figure demonstrates, even high flux test reactors, such as HFIR, are unable to create the environment necessary to qualify the SNTP engine; thus, a new nuclear ground test facility became a necessity for the success of the program.

Nuclear Fuel and Fuel Element Qualification

The PNT and the NET tests were carried out in the Annular Core Research Reactor (ACRR) at Sandia National Laboratory (SNL). While these tests were very important to the low risk, stepwise approach to testing and qualifying the nuclear fuel and fuel element, the capability of the ACRR and these tests, as shown in Fig. 4.7-3, are at conditions well outside of the operating conditions for a SNTP engine. Due to the power density and time limitations of the ACRR the fuel could not reach prototypical temperatures over the required flow range and, due to the size limitations, the NET tests were limited to subprototypic sized fuel elements. PIPET's role in qualifying the particle fuel and fuel element included the following items:

- Extending the understanding of the fuel and fuel elements response over the entire proposed operating range of the SNTP engine. The range refers to power densities, power excursion rates, temperatures, pressures, flow rates, and time of operation. Included in this understanding is the effect of spatial distribution.

- Fuel particle performance at operating conditions; e.g., mechanical integrity, fission product release, coating and kernel degradation rates, and failure modes.

- Determination of adequate safety margins for the fuel and fuel element by operating beyond the SNTP specifications.

- Structural response of a full-sized element.

- Determination of applicable thermal-hydraulic correlations.
- Determination of the flow distribution in an element.

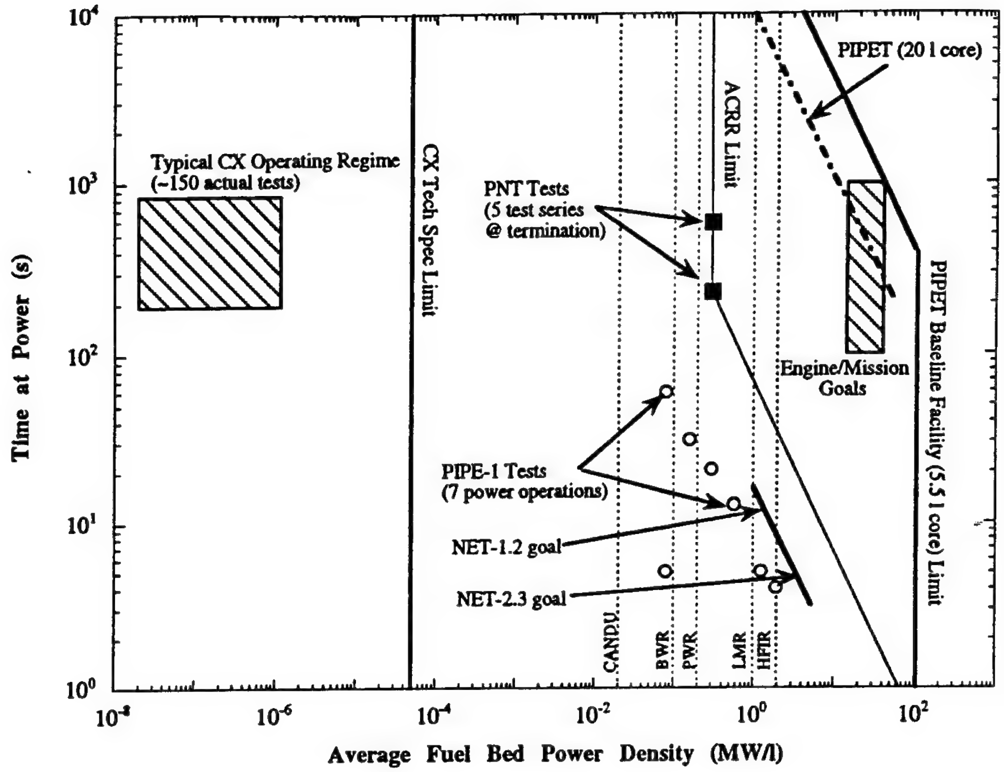


Figure 4.7-3 Plot of Goals of PIPET and SNTP Engine Compared SNTP Tests and Other Reactor Capabilities.

The reactor core used in PIPET to qualify the fuel and fuel element would be smaller than the core used in a SNTP engine and would not necessarily be prototypic in its configuration. The main reason for this is that the focus is on the fuel and fuel element, not the core and interaction between the fuel elements. The core would be designed specifically to accent the requirements to qualify the fuel and the fuel element. Other reasons also include the desire to minimize the cost of the test, test articles, and post-test examination, handling, and disposal; minimize the amount of nuclear fuel required for security reasons; and minimize post-test radiation levels impact on maintenance and further use of the facility.

Reactor Core Qualification

Once the fuel and fuel element are qualified as individual components it would be necessary to qualify a typical reactor core for an SNTP engine. The core would consist of prototypical fuel, fuel elements, moderator, shields, propellant plenums, and support structures. For the qualification tests the core would not interface with prototypical peripheral equipment, such as the propellant feed and control systems. The objective of these tests would be to determine the neutronic, thermal-hydraulic, and structural interactions between the reactor core components. Specifically, the tests were designed to:

- Determine the neutronic, power density, and temperature profiles in the core.
- Determine the flow distribution between the elements.
- Determine temperature dependent reactivity feedback.
- Benchmark and verify computer code modeling.
- Determine the stress and strain induced between the elements, moderator, and support structures.

The GTE was to be the culmination of the ground test phase of the SNTP program. It would integrate the qualified reactor core and qualified non-nuclear systems; including, the turbo-pump assembly, the propellant feed system, the nozzle (or a section of the nozzle), the integrated control system, and the pressure vessel. The GTE would be traceable to a flight engine; however, due to regulatory considerations, ES&H considerations, and the integration of the engine into the test facility the GTE would not have exhibited the exact characteristics of a flight engine. The purpose of the GTE was to demonstrate the operation of an integrated SNTP Engine at prototypical conditions. Based upon these series of tests a flight engine could be designed and built for flight testing.

4.7.3 The Ground Test Facility

In the initial phase of the SNTP Program PIPET was planned as a low-cost test facility dedicated to testing PBR fuel elements at prototypic conditions and supplying hot hydrogen to support other component tests. This basic concept was first discussed in the summer of 1988 and presented at a Preliminary Design Review (PDR) in 1989. In July 1991 a PIPET Concept Review Document was issued that estimated the cost of the facility and testing six (6) cores at $183M. In this document a preliminary cost estimate was presented for an effluent treatment system (ETS). The program realized that exhausting a potentially radioactive rocket plume to the atmosphere, as the NERVA/ROVER Program had done, was not acceptable to the government or the public. At this same time the program management also realized that the construction of the test facility required a dedicated project office with a Project Management Plan (PMP), a second PDR, a detailed procurement plan, and a comprehensive cost estimate. By August 1991 a Central Project Office for the Ground Test Facility was formed, led, and located at Sandia National Laboratory.

PIPET PDR

In March 1992 a second PDR was held and a SNTP PIPET PDR Data Package was issued. The PDR cost estimate of PIPET was still under $200M and the initial operational capability (IOC) was scheduled for the end of the third quarter of 1995 (end of government fiscal year 1995). The PDR Data Package included: (1) the requirements - the "A" Specification; (2) the PMP; (3) reactor systems studies and analyses; (4) a reactor design; (5) facilities design, including the EIT, the coolant supply system (CSS), and the effluent treatment system (ETS); (6) the instrument and control system design; (7) the safety analysis; and (8) a copy of

all the presentations made at the PDR. The design presented in the PDR assumed that the facility would be built on the "green fields" Saddle Mountain site of the Nevada Test Site. After the PDR, the analyses in support of and the preparation of the Environmental Impact Statement (ref. SNTP Final Environmental Impact Statement, May 1993) considered both Saddle Mountain and the Contained Test Facility at the Idaho National Engineering Laboratory.

The test facility described in the PDR was to be called the Saddle Mountain Test Site (SMTS) and was considered a national resource for the testing of NTP fuel elements, reactor cores, and engines. The planned full-scale SMTS would have had a number of testing facilities:

- A fuel element test reactor, PIPET.
- Facilities for the testing of the Ground Test Articles (GTA) and the Qualification Test Article (QTA).
- Facilities for the Engine Integration Tests (EIT), a non-nuclear facility for testing the integrated engine, but without a nuclear reactor.

This report summarizes the SMTS facilities design. The SNTP PIPET PDR Data Package is the document that presents the complete test facility design and supporting analyses, as it was prepared to support the PDR.

The PIPET facility, also referred to as the sub-scale facility in the PDR, would only have had the facilities absolutely necessary for the complete and safe testing of the fuel assemblies. The PIPET, or sub-scale facility, included:

- An earth-covered bunker containing all the control consoles associated with the SMTS. Access to the test station, activities in the test cells, and a system for video surveillance over the entire test station was to be controlled from this control bunker.

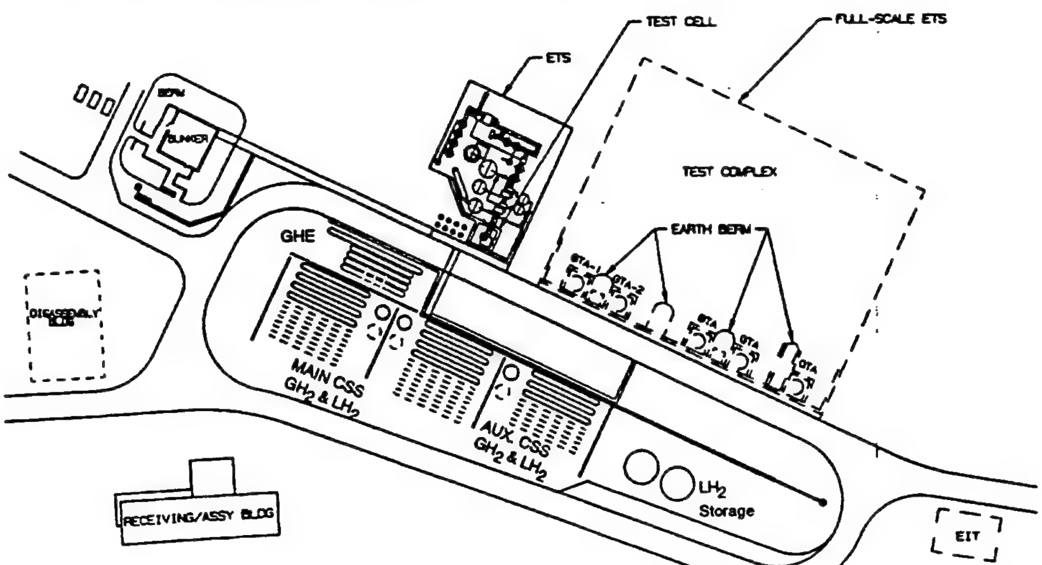


Figure 4.7-4 Saddle Mountain Test Site, PIPET and Expansion to Full-Scale Test Facility

- The data acquisition and instrumentation and control systems to operate the facility and control the experiments.
- A receiving and assembly facility for the assembly and non-nuclear testing of the sub-scale test reactor cores prior to being transported to the PIPET test cell.
- The PIPET reactor test cell.
- The Coolant Supply System (CSS) which supplied the cryogenic hydrogen and helium to PIPET.
- The Effluent Treatment System is (ETS) designed to remove all particulate and radioactive contaminants from the PIPET exhaust stream.
- A remote inspection and maintenance system for the evaluation of the PIPET test reactors in a high-radiation environment.
- Road, services (utilities), and the necessary security systems.

The site plan for the sub-scale facility would have accommodated the eventual planned expansion to the full-scale facility. The full-scale SMTS facility would have included the following upgrades to the sub-scale facility:

- A new building for engine test cells for testing GTA's and QTA's.
- A separate console in the control bunker for each additional engine test cell.
- Expanded and/or additional CSS's and ETS's for the engine test cells.
- Additional Remote Inspection and Maintenance system for the engine test cells.
- The EIT facility.
- A disassembly facility for post-irradiation evaluations (PIE).
- Additional roads, utilities, security, and surveillance to accommodate the engine testing.

The layout of the sub-scale SMTS, PIPET, with projected full-scale upgrades is shown in Fig. 4.7-4.

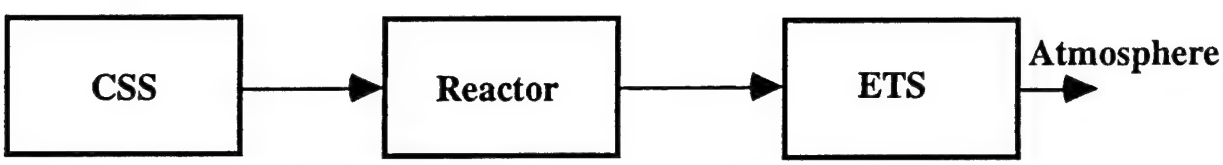


Figure 4.7-5 Relationship of Process Fluid Systems to Test Reactor

In support of the safety effort the SNTP PIPET PDR Data Package includes the following items:

- A rough draft of the Safety Policy, Implementation Guidelines, and Goals for the Space Nuclear Thermal Propulsion Program.
- An estimate of the fission product release fractions from the particle fuel due to diffusion during operation.

- An estimate of the emissions and dose estimates for operation of PIPET and the GTA under various operational and environmental scenarios.
- A Preliminary Accident Analysis.
- A copy of the input for the Environmental Impact Statement.
- Miscellaneous items including seismic consideration, climatological data, and beryllium concentration guidelines.

PIPET Process Fluid System

The sub-scale test reactor interfaces with the process fluid system, the CSS and the ETS, are shown in Fig. 4.7-5. The coolant supplied by the CSS passes through the core and surrounding structure cooling the reactor. While passing through the core the hydrogen coolant will pick up radioactive particulate from anticipated diffusion and/or from the fuel failures. Upon exiting reactor the hot coolant enters the ETS, which cleans out the majority of radioactive material from the stream before it is exhausted to the atmosphere. The nominal design point for the PIPET reactor's process fluid system is 220 MW_t for 500 seconds, or a total energy capacity of 110 GJ, and a maximum thermal power of 550 MW_t.

The primary functions of the CSS are:

- To cool the reactor fuel and structure during operation.
- To remove decay heat from the reactor fuel and structure after reactor shutdown.
- To provide support for activities such as purging, inerting, chill down, fluid transfer, and vessel fill.

Cryogenic hydrogen is the primary reactor coolant and the coolant for the surrounding reactor structure during operation: the main flow and the auxiliary flow, respectively. The PIPET reactor, designed to operate over a range of power levels, requires the coolant flows to be supplied over a range of temperatures and pressures to match the reactors operating power and the desired test conditions. Both the main flow and the auxiliary coolant flows are supplied to the PIPET reactor via a blowdown system. Prior to operation the system is purged from pressurized helium tanks. The insulated, cryogenic main run tanks are filled with LH_2 from the site's storage dewars. The LH_2 in the run tank is maintained at a pressure exceeding the required downstream pressure by high-pressure GH_2 at ambient temperature. The high-pressure, ambient temperature hydrogen gas is also mixed down stream with the cryogenic LH_2 in a mixer to supply the reactor with a flow of H_2 at the desired temperature and pressure.

After the reactor operation the reactor must continue to be cooled due to the radioactive decay of fission products and their daughters. Based upon the proposed operation of PIPET the post-operation cooling may have to continue from days to weeks. The fission product decay power is a function of the power of operation and the time of operation and decays away in an exponential manner. The post-operation cooling would be initially with hydrogen, but eventually would be transitioned to helium at lower powers: helium is not as an effective heat transfer medium as hydrogen and the transition point would be determined by flow considerations. Like the hydrogen, for the sub-scale facility the helium would be supplied to the reactor by a blowdown system.

The planned upgrade to the full-scale facility included a pumped CSS. The pump could be either a site work-horse pump or a turbo-pump assembly for the integrated engine tests. The upgrade to the CSS also included increasing the storage capacity for the GH_2 and helium, and pumping LH_2 from the storage dewars to accommodate larger thermal powers and longer run times. For the most part, in upgrading from the sub-scale facility to the full-scale facility the CSS is expanded, making use of the CSS already in place.

As shown in Fig. 4.7-5, the CSS supplies cryogenic hydrogen coolant to the test article; i.e., the PIPET reactor. The PIPET reactor is sited in a reinforced concrete test cell, located partially below grade: the walls of the test cell provides radiation shielding. PIPET is a thermal-spectrum reactor using highly-enriched uranium particle fuel with a beryllium moderator. The reactor has multiple barriers to prevent release of radioactive material to the surrounding environment. The test article (reactor core) is confined in two carbon-carbon pressure vessels, the Canister Assembly and the Rod Support Barrier, and a metallic pressure vessel, the Confinement Vessel. The carbon-carbon barriers protect the Confinement Vessel from any unanticipated pressure pulses and the Confinement Vessel contains the release of any radioactive material. The Rod Support Barrier is surrounded by a graphite reflector which contains rotating, neutron absorbing, reactivity control drums.

At the time of the PDR PIPET was a test bed for testing fuel elements. The upgrade to the full-scale SMTS required new test cells for the engine tests, as shown on the site layout, Fig. 4.7-4.

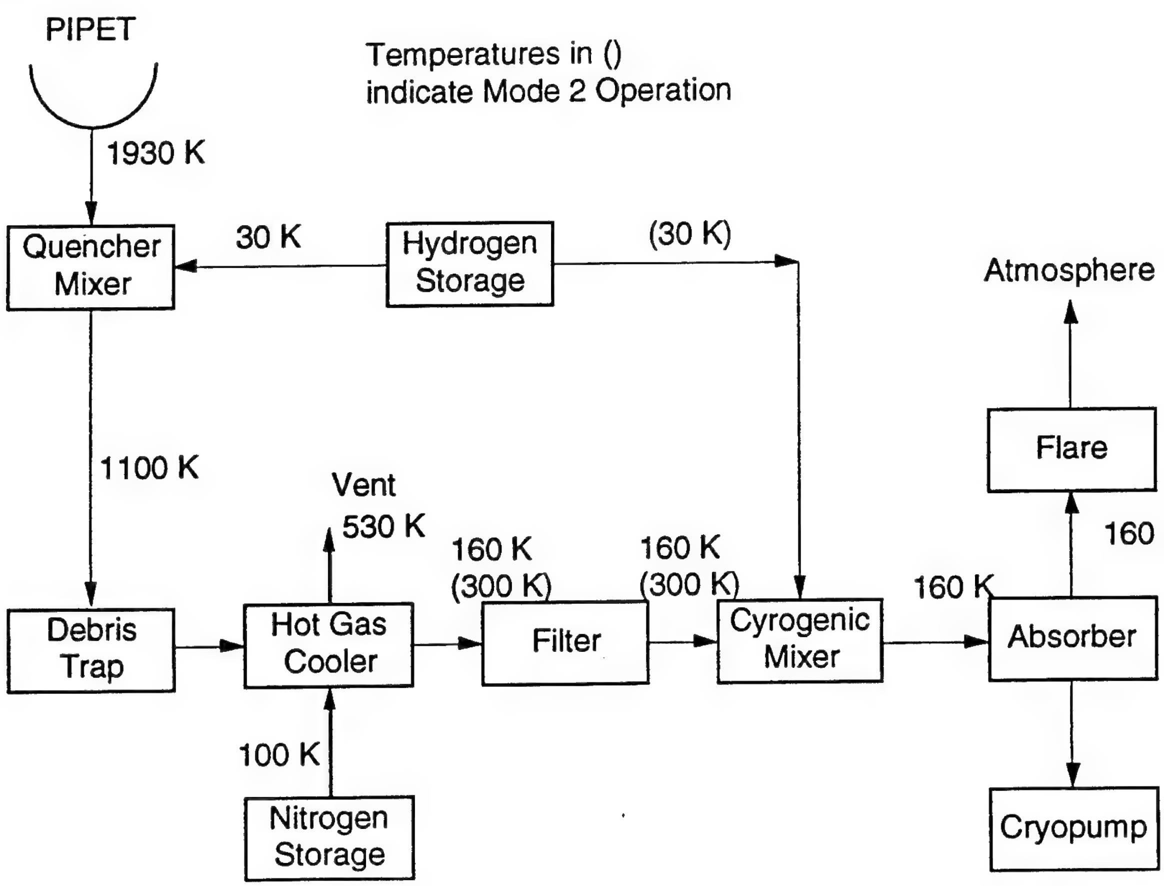


Figure 4.7-6 Flow Diagram for PIPET ETS

After the hydrogen (or helium) coolant passes through the reactor it enters the ETS. The functions of the ETS are:

- To remove radioactive contaminants from the effluent stream so that the gaseous waste can be flared while maintaining atmospheric emissions within applicable limits.

- To cool the hot gas to temperatures that allow processing using conventional methods and materials.

Figure 4.7-6 is a flow diagram of the PIPET ETS indicating the temperatures at each component for both design modes of operation. In both modes of operation the hot hydrogen stream exits PIPET into the Quencher Mixer where it is cooled by being mixed with a stream of cryogenic hydrogen. Exiting the Quencher Mixer the hydrogen stream enters the Debris Trap. The Debris Trap is used to capture the debris from destructive testing of the test article to prevent unnecessary contamination of the downstream components. From the Debris trap the stream is cooled in the Hot Gas Cooler, a heat exchanger with liquid nitrogen flowing on the secondary side. The nitrogen from the Hot Gas Cooler is vented to the atmosphere. The stream exits the Hot Gas Cooler and enters a particulate filter where 99.9 % of all the particulate material is removed from the stream. Exiting the filter the stream enters the Cryogenic Mixer. In one mode the stream passes through the Cryogenic Mixer and in second mode the stream temperature is reduced by mixing liquid hydrogen with the process stream. In either mode the process stream enters the Absorber at the design temperature of the Absorber. The Absorber removes 99.5 % of the iodine, and other halogens, and the noble gases. At the end of operation a cryopump is used to remove the halogens and noble gases from the Absorber's activated carbon bed for storage in a collection bottle. The clean process hydrogen stream is then flared and vented to the atmosphere.

Because of the program's plans at time of the PDR to do destructive testing in PIPET and due to sizing considerations, the PIPET ETS was not suitable for the full-scale upgrades that would test full cores and engines. Thus, to upgrade the site for engine tests a new ETS was required. It was not certain if one ETS would accommodate all the planned engines tests (GTA's and QTA) or if a new ETS was required for each test cell. The notion at the time was that if there was an engine test failure that would result in a core disruption and a subsequent displace of core material into the ETS, and if the ETS design was similar to the PIPET ETS, the ETS would not be suitable for additional engine tests.

The SNTP Program was, at the time of the PDR, considering a planned destructive test in PIPET. The program also considered the possibility of unplanned core disruption events in both PIPET and the engine tests. This was not irresponsible or unprecedented, as exhibited in the NERVA/ROVER nuclear thermal propulsion program:

- In 1965 the NERVA/ROVER program conducted the Kiwi-TNT (Transient Nuclear Test) which deliberately destroyed a Kiwi-B-type engine in a fast excursion test.

- During the NERVA/ROVER program 22 reactor/engines were built and tested, a number of these tests resulted in damage to the nuclear assembly.

One of the major differences between the NERVA/ROVER program and the SNTP program was an economic one brought on by a change in political climate and centered around the ETS. The NERVA/ROVER program did not employ an ETS. When a test resulted in a failure the exhaust plume, often including radioactive material, was exhausted to the environment of the Nevada Test Site: this was acceptable and not out of the norm for the time (at least early in the program) considering above ground nuclear weapons testing. However, by the time of the SNTP program exhausting radioactive material to the environment of the test site was unacceptable and not allowed by the government: an ETS was necessary and demanded. Cost estimates of the SMTS, subsequent to the PDR, indicated that the cost of the test site could very easily be driven by the cost of the ETS and the preservation of the environment.

4.7.4 Post-PDR Activity

Even during the preparation of the PDR the program was undertaking an in-depth cost estimate of constructing and operating the SMTS through decommissioning and decontamination. This cost estimate caused concern for the program management as to the affordability of the program: life-time cost estimates for the SMTS exceeded $1B. After the PDR was complete and the subsequent cost estimate was presented, the program undertook an effort to understand what drove the cost for the SMTS. The results of this effort identified ETS as one of the main cost drivers for the test site. This hinged mainly on the fact that the full-scale facility required a new and larger ETS than the sub-scale facility required. It became obvious that if the engine tests could use the same, or expand, the PIPET ETS the cost of the facility would be reduced considerably.

After this evaluation the program explored lower cost alternatives to the full-scale facility presented in the SNTP PIPET PDR Data Package. This included looking at facility designs that used, or expanded, the ETS from the sub-scale for the full-scale facility, a reduction in the planned test program, and the use of other facilities for the post-irradiation examination. The goal of this revised facility was still to provide a national test facility for nuclear thermal propulsion, a facility for testing and qualifying PBR fuel and fuel elements, and to ground test an integrated engine. It was recognized that the ground test article would not be the same as the eventual flight engine, but would be similar, smaller, but most importantly, traceable in design and operation to the eventual flight article. Recognizing this differentiation the GTE designation was changed to the Demonstration Engine.

The result of this effort to define a new ground test facility suggested a modified PIPET, a reduced test plan, and the contracting of the post-irradiation examination to a third party. The PIPET Confinement Vessel would be designed to be large enough and flexible enough to house a reactor core and its associated moderator, reflector, and control devices or a scale-down integrated engine. The CSS and ETS would be designed to accommodate the energy requirements of the engine tests. The test program was reduced to include fewer fuel and fuel element qualification tests, excluded any destructive tests (to avoid damage to the ETS), and test one integrated engine. This revised test plan resulted in a significant reduction in the cost of the proposed test site. There were additional considerations of more focused, lower cost tests for qualifying the fuel and fuel elements or working with the New Independent States of the

former Soviet Union to use test facilities from their Nuclear Rocket Engine program. However, before these plans could be investigated further the program was terminated.

4.7.5 Summary and Conclusions

By reviewing the SNTP PIPET PDR Data Package in depth a reader of this document will appreciate the extent and the amount of work that was completed in preparation for the PIPET PDR. It is accurate to characterize this effort as a well organized, well defined major construction project that made significant progress. The accomplishments of the PIPET Project Team included:

- Establishment of a PIPET Central Project Office (CPO) to coordinate the SNTP Program's efforts.

- The CPO issued a Project Management Manual, established a Work Breakdown Structure, and instituted configuration control on the project's drawings, designs, etc.

- The formation of a working facilities engineering team that included DOE Nevada Operations Office, Sandia National Laboratory, Aerojet Propulsion Corp., Garrett Fluid Systems, Raytheon, U.S. Army Corps of Engineers, and Fluor Daniels, Inc.

- Issued an "A" Specification for the SMTS.

- Completed a Preliminary Safety Assessment.

- Title II design of the sub-scale facility and items common to the sub-scale and full-scale facility, including all drawings, systems descriptions, and design calculations for all systems and buildings, except the reactor and its I&C.

- Conceptual design for the full-scale upgrades.

- A detailed cost estimate for the construction and operation of the sub-scale facility. A preliminary cost estimate for the full-scale construction, operation, and site de-commissioning and decontamination.

- Initial site preparation tasks for the SMTS at the Nevada Test Site; e.g., site evaluation, utility identification, environmental issues, access evaluation.

Initially, PIPET was envisioned as a small, low-cost, SNTP-specific experiment for testing and qualifying PBR fuel and fuel elements. The demands by other agencies, DOE and NASA, resulted in a national test facility for NTP fuel, fuel elements, and engines. Its size out grew the SNTP Program's ability to secure the funds for such a large construction project. Though the demands were placed upon the SNTP Program to expand the facility's scope and the SNTP Program's management tried to coordinate tri-agency, DoD-DOE-NASA, support and funding, adequate funding support for the national ground test facility was not obtained.

4.8 WBS 1.8 Supporting Test Facilities

4.8.1 Overview

A development program such as SNTP, where technology was being advanced on several fronts, required diverse supporting test facilities. For much of the early experimental work, existing laboratory facilities were utilized at Sandia National Labs, Brookhaven National Lab, and the industrial contractor facilities. However, as the program moved forward toward the hardware development phase, new, dedicated, non-nuclear test facilities were identified. The major new test facilities that were planned and in various stages of readiness were:

- The San Tan hydrogen test facility.
- The SNTP System Integration/Simulation Laboratory.
- The Engine Integration Facility.

The San Tan hydrogen test facility is located about 20 miles outside Tempe, AZ and was

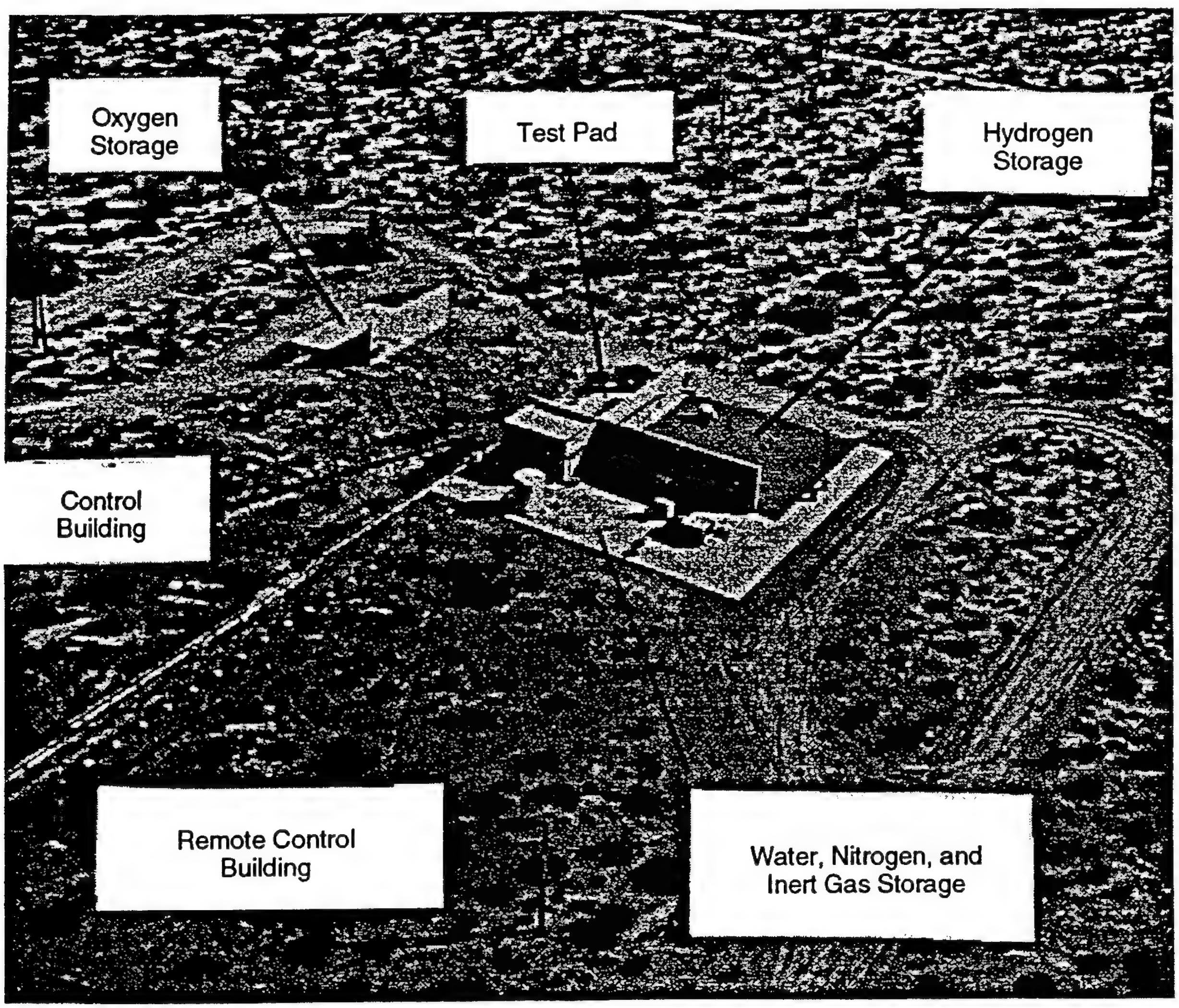


Figure 4.8-1 Aerial View of San Tan Facility

being built and (to be) operated by Allied Signal Fluid Systems Division (FSD). This facility was specifically designed and built to provide the SNTP program both hot and cold hydrogen test capability. Its principal purpose was to allow design, development, verification and qualification of the Propellant Management System (including the TPA) and other SNTP components exposed to a hydrogen environment, including developing materials for the program. The facility was to include the capability to support engine definition and analytical modeling, including two-phase flow, start transient and code benchmarking experiments.

The SNTP System Integration & Test Laboratory (SITL) was a Grumman owned facility located in the William Schwendler Development Center at the Grumman complex in Bethpage, NY. Equipped with new, modern real-time computing equipment and hardware-in-the-loop capabilities, the SITL was being used to design and develop the integrated control system for SNTP. The facility, which was formally dedicated in December of 1992, was to play an important part in the development of a totally integrated engine system and in the development, verification & validation of operational software.

The Engine Integration Facility was in the planing stages only and had been designated to be located at the nuclear test facility and used to perform system and component hardware integration and non-nuclear testing of the various SNTP test articles, prior to nuclear testing.

4.8.2 San Tan Hydrogen Test Facility

Introduction

The San Tan hydrogen test facility was being constructed as a versatile test facility used primarily for research and development of subsystems and components for the SNTP program. The San Tan hydrogen test facility was part of the remote San Tan test site located 20 miles southeast of Allied-Signal Aerospace Company, Tempe, Arizona. The San Tan test site has been in operation for over 30 years and was constructed for testing aerospace systems and components produced by Allied Signal divisions that require the safety and isolation provided by this remote site.

Located on 225 acres of land leased from the Gila River Indian Community, the San Tan test site lies within the Gila River Indian Reservation and is in a small dry valley on the west side of the San Tan Mountain more than 1.5 miles from the nearest structure. The hydrogen test facility was constructed on a newly leased 110 acre parcel of land adjacent to the existing 115 acres. As shown in the aerial view in Figure 4.8-1, the presently constructed facility structures encompass approximately 15 acres with adjacent acreage reserved for future expansion.

The San Tan hydrogen test facility incorporated features that emphasize personnel safety and hardware protection. The safety aspects of the test facility design include separation distances in accordance with DOD (Department of Defense) safety design standards, ASTM and NFPA design practices for cleaning and selecting materials used in oxygen and hydrogen service. An example of the emphasis of safety design is the heavy duty steel-reinforced concrete blast walls constructed to isolate all fluid storage from the test cell and personnel-occupied control buildings. The facility is completely fenced for security and could

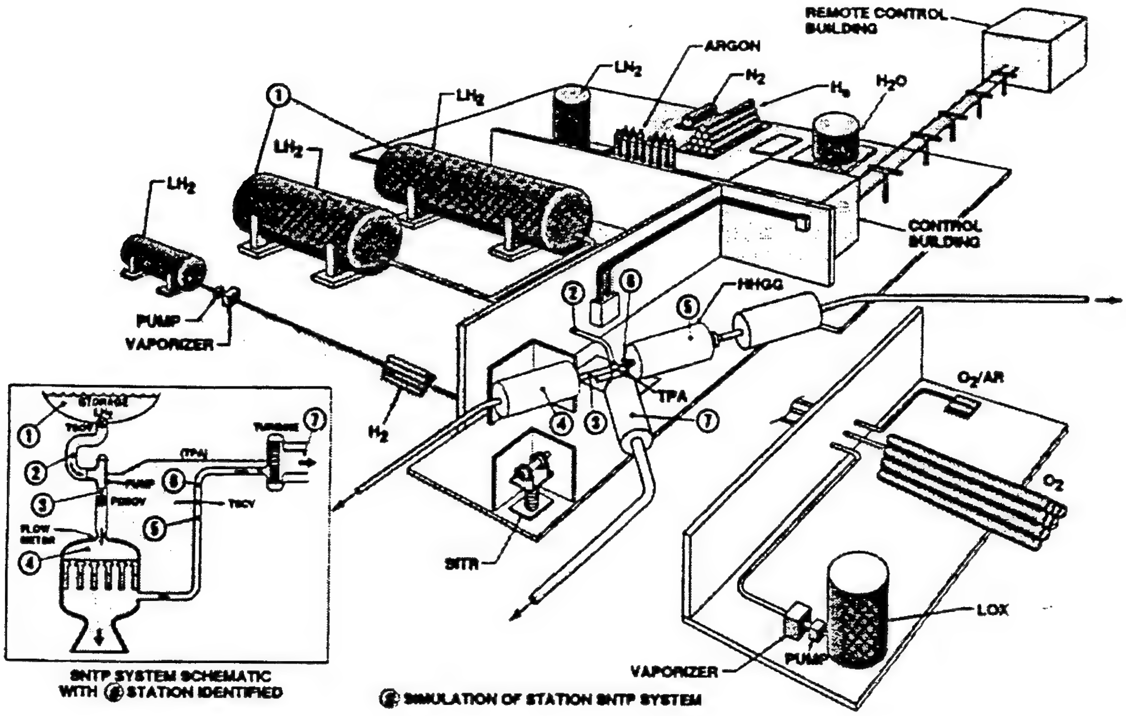


Figure 4.8-2 Hydrogen Test Facility Layout

easily be secured to a higher level with additional fencing and protective measures.

The San Tan test site is in full compliance with all applicable environmental regulations. Wastes are disposed of at licensed and approved treatment, storage and disposal facilities and are transported by way of licensed hazardous waste transporters.

Hydrogen Test Facility Description

The hydrogen test facility layout is illustrated by the isometric schematic shown in Figure 4.8-2. This schematic presents the general layout of the facility and displays the method used to simulate the fluid conditions of the SNTP system. Stations along the flow path of the fluids in the SNTP system are numbered on the inset schematic and simulated in the test facility as identified by a corresponding station number.

The facility consists of an open-type test cell, on-site control building, remote control building, hydrogen storage area, oxygen storage area and inert fluid storage area. The storage areas and control buildings are separated from the test cell by 16-foot high, 1-foot thick, steel-reinforced concrete blast walls.

Hydrogen Test Facility Capabilities

The San Tan hydrogen test facility was designed and constructed to provide for testing components and integrated subsystems of the SNTP program by simulating the inlet and outlet conditions for each of the indicated stations along the fluid path in the engine system. To accomplish this goal and provide support fluids to the facility a variety of fluids were required.

Test Capability (3000K/1000psi)	Equivalent energy (Therm.)	Energy Source	Required Electrical Supply	Critical Issues
Low-flow 5g/sec	250kW	100% Electrical	400kW	None
Sub-scale 50g/sec	2.5MW	90% Combustion 10% Electrical	400kW	Dev./Fab of integrated heater
Full-scale 700g/sec	35MW	90% Combustion 10% Electrical	6MW	Dev./Fab of integrated heater

Figure 4.8-3 Phased Development of Hot Hydrogen Test Capability

Hydrogen test capabilities range from the cryogenic liquid phase to extremely high-temperature gas. Cryogenic hydrogen could be supplied for saturated liquid temperatures at atmospheric pressure to approximately 100 psia. The storage capacity was 13,000 gallons with capabilities of adding storage tanks in increments up to 18,000 gallons each. Flow rates were limited by the 8-inch discharge line which would allow 100 gal/s flow with relatively low pressure drop. Test durations would be limited only by the amount of fluid storage at the beginning of a specific test sequence. High-pressure cryogenic hydrogen testing could be accomplished by means of cryogenic pumps or pressurized tanks for a blowdown-type test. For extremely high-temperature hydrogen testing, a heat-exchanger-type heater was being developed to provide hot hydrogen at temperatures up to 2750 °K at pressures up to 1000 psia and flow rates from 0.05 lb/s to 2.5 lb/s. These high temperatures would be generated by a hydrogen and oxygen combustion process as a heat source. An electrical superheater could be incorporated to supplement the combustion heater depending on the maximum gas temperature requirement. Hot helium could also be generated with the same equipment with an adequate supply of helium.

State-of-the-art sensors were provided to measure all parameters necessary to define the performance of the facility and test articles. Pressures are measured by pressure transducers selected for the appropriate range to ensure maximum accuracy. Flow rates are measured by means of flow meters such as delta pressure devices, turbine meters, positive-displacement meters or other devices that are applicable for the flow accuracy or transient response. Temperature measurements are determined by applying thermocouples for all temperature ranges and pyrometers for high-temperature ranges where the article can be viewed by the pyrometer sensor. Other high-temperature measuring devices were being developed as part of the test effort to directly measure the extremely high temperatures being generated as a requirement of the test conditions of systems such as the SNTP.

Phased Approach to Develop Hot Hydrogen Capability

Study and analysis efforts to develop a phased approach to hot hydrogen testing at San Tan had just been competed when termination proceedings began. This approach, summarized in Figure 4.8-3, would have quickly provided an initial capacity to test at 5 grams per

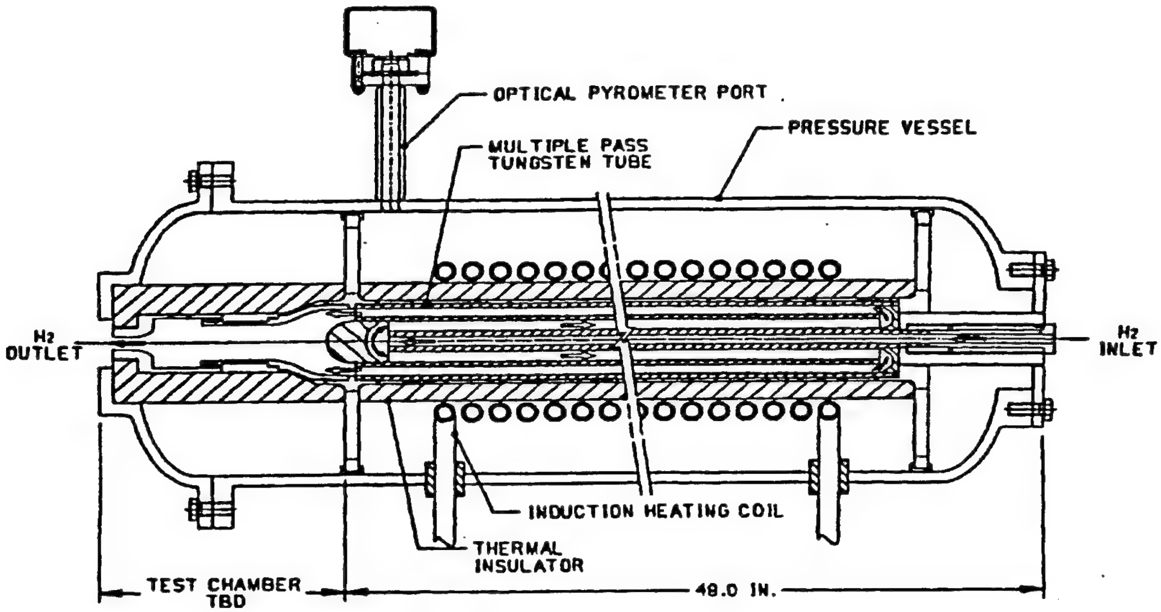


Figure 4.8-4 Low-Flow Hydrogen Heating Concept

second at 3000 K by using an electrical induction heater. The induction heater, Figure 4.8-4, in addition to providing hot hydrogen at low flows for initial material testing would have served as a design base for scaling to larger sizes. The larger flow rate induction heater would then be used to augment the combustion based, basic concept.

The basic concept of a tungsten heat exchanger that used combustion of hydrogen and oxygen as the primary energy source is shown schematically in Figure 4.8-5. The detail design of this device was 90% complete at termination. The tungsten material had been purchased and the rhenium coating process developed. The rhenium coating was needed to protect the tungsten structure from the superheated steam generated by H_2 - O_2 combustion. This device was designed to have an exit temperature of 2750 K. The electrical induction heater would have then added the final thermal energy increasing exit temperature to 3000 K.

Hydrogen Test Facility Control and Data Acquisition

The control and data acquisition system was designed and installed with the requirement of having flexibility for continuing concept of establishing a versatile test facility. This flexible control concept is centered on the selection of an industrial computer and integrated support hardware identified as a PLC (programmable logic controller). The computer and PLC are both operator friendly and have easy-to-use software programs.

This control and display logic is shown in simplified form in Figure 4.8-6. The monitors, including the touch-screen monitor, display data that allows the test operator and crew to view critical performance parameters, limit signals and generate critical point alarms during a test sequence. A conveniently located control panel is provided to allow the test operator to select a preprogrammed emergency shutdown sequence in event of component failure or select a controlled extreme emergency shutdown that requires a quick acting abort cycle.

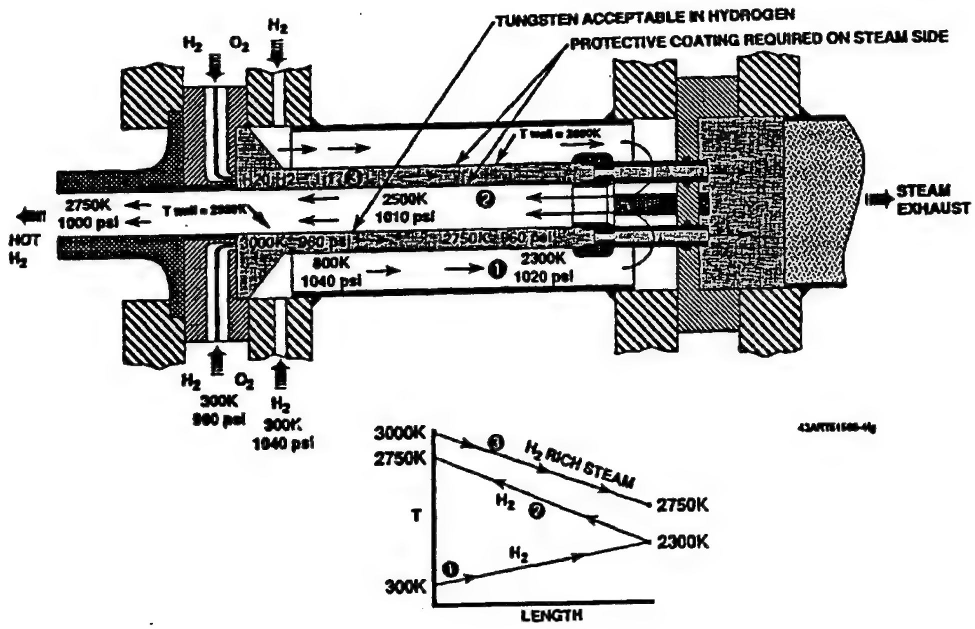


Figure 4.8-5 Hot-Hydrogen Gas Generator (HHGG)

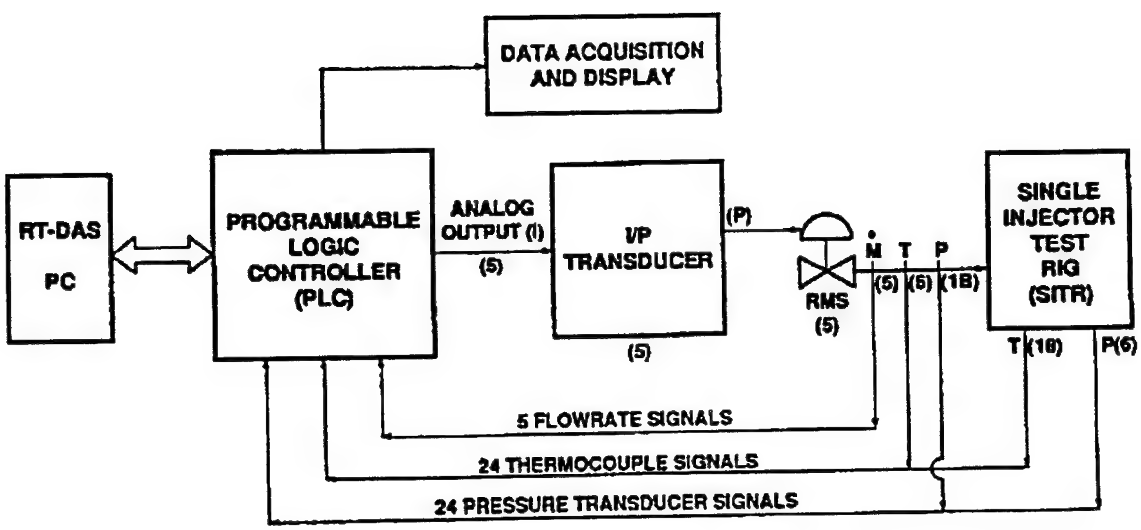


Figure 4.8-6 Instrumentation & Electronic Controls

Digital data acquisition capabilities are built into the electronic equipment to allow for storage of digital data as well as signal conversion to drive external recorders such as strip chart recorders and other peripheral recording devices or other monitoring devices that could be required. The capability of the acquisition system allowed for simultaneous monitoring of 40 analog channels and 100 digital channels.

4.8.3 System Integration/Simulation Laboratory

In support of the SNTP program, Grumman established a 4000 sq ft facility within the Schwendler Development Center in Building 14, Bethpage, NY. The System Integration Test Laboratory (SITL) was a vital asset in supporting development and integration of digital control systems, advanced instrumentation, simulations and operator training systems for the SNTP program. The lab was a key element in the successful development of the flow control system developed for nuclear element tests at Sandia National Laboratory. The laboratory consisted of three major components:

- Real-time computer facility containing various special purpose computer resources including Applied Dynamics AD-100 and analog computers, which played a vital role in the development of the SNTP thermal/fluid and neutronic models.

- Software development facility containing SUN, Silicon Graphics and microvax work-stations and various Mac's and PC's. Support of the NET flow control software, safety shutdown and instrumentation was supported within this facility. Also performed were detailed thermal/hydraulic and nuclear code generation for real-time simulation/analysis.

- Hardware integration facility where NET hardware was qualified, tested and integrated with the system. This included NET motor testing, sensor instrumentation integration and cryogenic test of components to be used in the NET experiments.

4.8.4 Engine Integration Test Facility

The Engine Integration Tests (EIT) were planned for the test facility at the Nuclear Test Site (NTS). The capabilities and facility description of the NTS are found in Section 4.7 of this report. The goal of EIT was to perform a comprehensive series of cold flow (no reactor) tests to characterize, integrate, and qualify the engine feed system, propellant management system, and engine components prior to demonstration engine firings. This would develop a non-nuclear database and confidence of operation to allow proceeding to the nuclear engine demonstration tests.

The full scale EIT would start with component checkout and system buildup and conclude with a full flow mission duration test with prototypical turbopump and control system demonstration. The EIT would utilize a full scale reactor flow simulator (RFS) which would duplicate the reactor cold flow internal passages and thermal mass. This unit would be well instrumented to verify predicted flow distribution and pressure drops. Purge and chilldown procedures were to be developed and followed by hardware and software checkout

under progressively built up flow conditions. Operational margins and design limits of the engine systems with RFS during off-design conditions such as throttling would be determined. Initially, flow was to be supplied by facility pressurized tanks and then by a facility pump or a workhorse prototype turbopump. These tests would be succeeded by start system development work. The progressive integration of the actual prototypical turbopump would complete the test series. The turbopump was to be powered by a hot hydrogen gas generator (HHGG) being developed by the program. These tests would have verified the EIT specifications, performance requirements, and test procedures in addition to the controls and hardware for testing with the reactor.

4.9 WBS 1.9 Supporting Technologies

4.9.1 Overview

Supporting Technologies were a collection of activities that in general were either; special emphasis technology development activities; or activities that were broad in scope and applicable to a number of SNTP activities. Examples include:

- Materials
- Advanced Instrumentation
- Modeling & Analysis
- System Simulation
- Integrated Control System

The design and development of a high temperature (i.e. 3000 K), hydrogen cooled, high power density particle bed reactor, capable of very rapid start-up, represented a major leap forward in nuclear system technology. Application and extension of state-of-the-art technologies, and effective utilization of modern engineering tools, techniques and computing capabilities were critical to the success of this effort. Each of the 5 supporting technologies identified above received some degree of attention during the SNTP program.

4.9.2 Materials

A key element to the success of the SNTP program was the development of materials that satisfied the requirements imposed by the SNTP design. Materials that are capable of retaining mechanical strength and integrity at extreme temperatures and pressures in a hydrogen environment for moderate periods of time were required. In addition, these materials must be compatible with the engine's radiation environment. Previous research has shown that carbon-based materials offer the only near-term solution to this need, although the desired operating conditions exceed what has been demonstrated to date.

The effort supporting materials R & D covered generic research and development planning of graphite and carbon-carbon substrates and coatings which could be used at temperatures up to 3000 K in a high pressure hydrogen environment. These materials were likely to be used for the nozzle, turbopump, ducting, hot frit and ground-test facilities.

Since specific materials properties for the LV03 conditions were not well defined, this

effort was to be initially focused on five elements. These were:

- Carbon-Carbon Mechanical and Thermal Properties
- Carbon-Carbon Thermal Cycling Tests
- Nuclear Radiation Effects
- Coating Effectiveness
- CIS Material Technology Evaluation.

Preliminary evaluations of the effects of nuclear radiation and thermal cycling were made utilizing published data. The results of these evaluations are discussed in Section 4.4.6. Tests were planned to confirm these results and/or obtain additional data.

Testing to extend the mechanical properties data base of carbon-carbon to ~ 3000 K was underway at Hercules, and their subcontractor Southern Research Institute (SoRI). Hercules' UHM carbon-carbon, which was being developed for the turbine and pressure vessel/nozzle, was the material used.

The test program was broken into two phases. In Phase I several carbon-carbon processing approaches were screened and evaluated. Room temperature (RT) properties were obtained and tension strength goals were achieved. Based on the Phase I results, a hybrid chemical vapor infiltration (CVI) and pitch impregnation process, with five densification cycles, was selected for the next phase. Two test cylinders were fabricated, from which samples would be obtained The first cylinder was completed and tests performed. The second cylinder was in the final stage of fabrication when the effort was halted.

The Phase II mechanical and thermal properties testing at SoRI was essentially complete when funding was stopped in May 1993. The test matrix and status is shown in Figure 4.9-1. Evaluation and documentation of the data was not accomplished except for the thermal properties shown in Figure 4.9-2.

No. of Specimens	Test Type	Test Conditions	Status
3	Hoop tension	2755 K (inner wall)	To do
2	Hoop tension	RT	Complete
3	Radial shear	2755 K	Complete
3	Radial shear	3035 K	Complete
3	Axial compression	2755 K (mid wall)	Complete
3	Axial compression	2755 K (edge)	Complete
3	Axial compression	3035 K (mid wall)	Complete
3	Axial compression	3035 K (edge)	Complete
2	Radial thermal conductivity	365 - 3035 K	Complete
2	Axial thermal expansion	145 - 3035 K	Complete

Figure 4.9-1 Mechanical and Thermal Properties Test Matrix

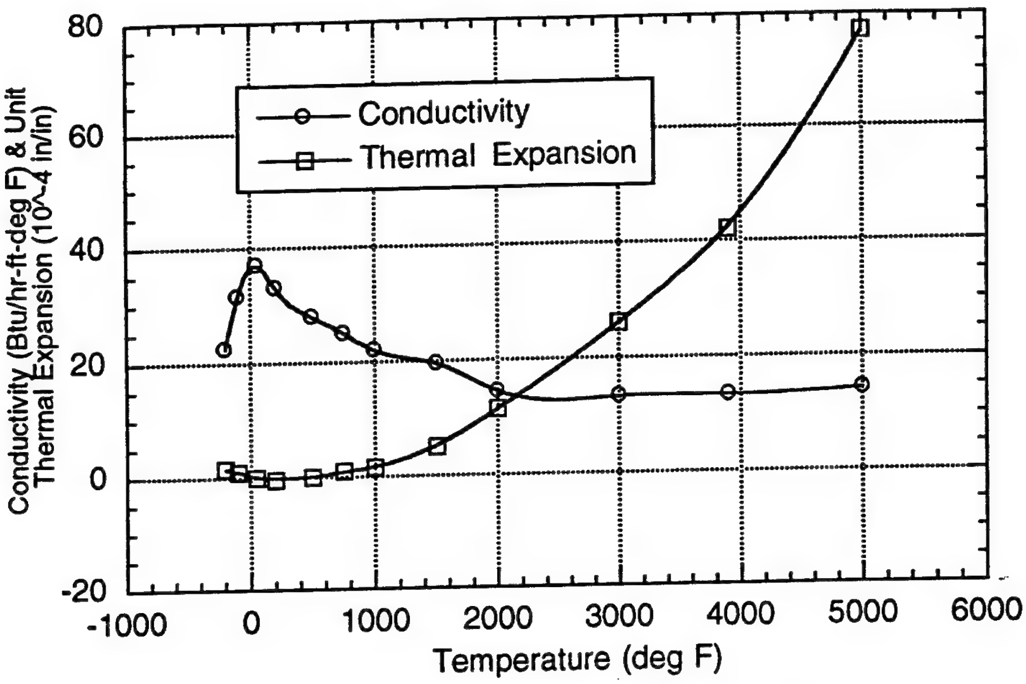


Figure 4.9-2 Thermal Properties of Carbon-Carbon

Another major activity in the materials area was the development of coating systems. The efforts related to coating the fuel particles were done within that work package (WBS 1.5) primarily by BNL and B&W. The coating activities related to the non-fuel components were coordinated by Grumman to make the data available for all the carbon based components - graphite and carbon-carbon hot frits and carbon-carbon pressure vessel, nozzle and turbine.

The primary organizations for development and evaluation of the non-fuel coatings were BNL and Hercules. BNL concentrated on the hot frit development. The capability at BNL was limited to testing small samples at prototypic temperatures, low to moderate pressure, long duration and low hydrogen flow.

Results of BNL's hydrogen erosion tests of AXF-5QI graphite, and carbon-carbon with tantalum carbide and niobium carbide coatings are shown in Figure 4.9-3. Based on these results, a tantalum carbide coating system was baselined for the hot frit. Furthermore, evaluation of several coating processes concluded that the chemical vapor reaction process (CVR) produced more effective coatings than did the lower temperature chemical vapor deposition process (CVD). Hence CVR was baselined for the hot frit as well.

Testing and evaluation of carbon-carbon coatings applicable to the nozzle and turbine was the primary responsibility of Hercules with testing planned at BNL and other potential locations, e.g., Phillips Lab/EAFB and BIRL Industrial Research Lab at Northwestern University. Coatings being considered for these non-reactor components included CVD and CVR of niobium carbide, tantalum carbide and tantalum hafnium carbide. The first coatings produced were CVD of niobium carbide on small samples. Acceptable coatings were achieved, but no test results were obtained prior to halting program activities in the second quarter GFY '93.

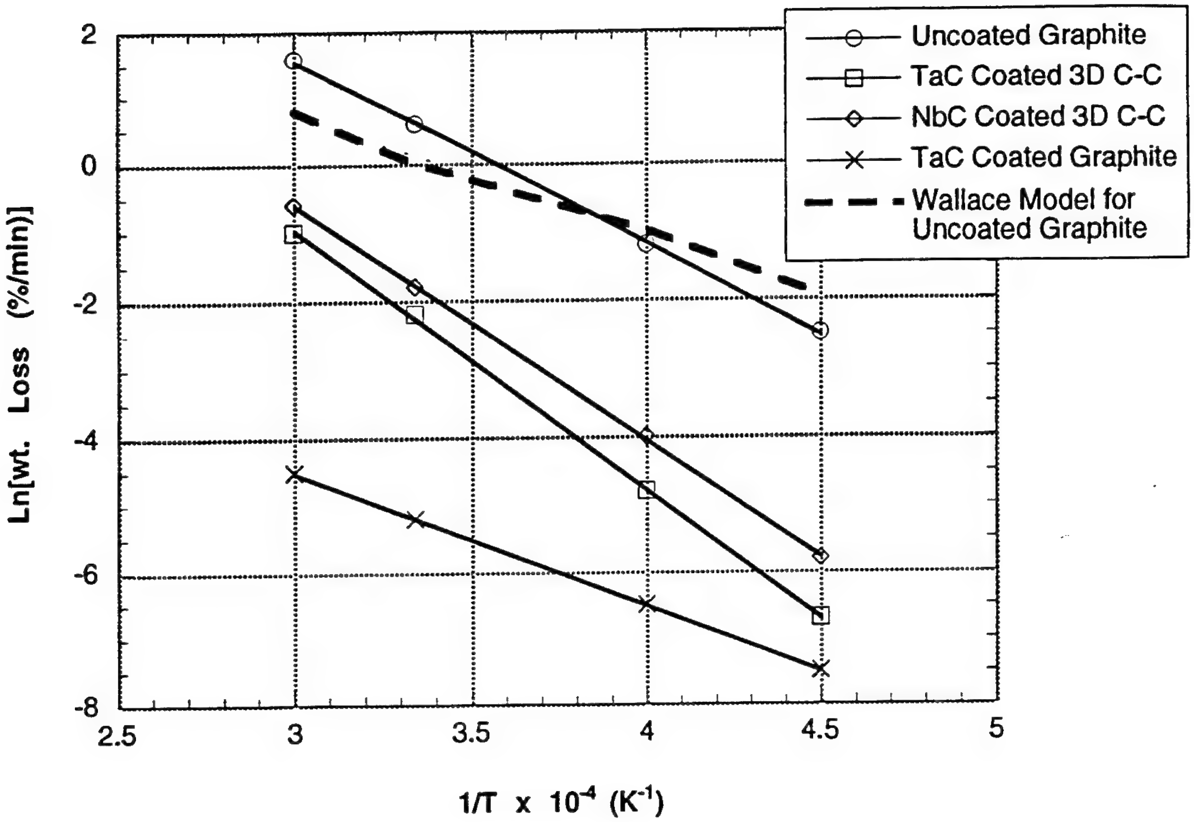


Fig. 4.9-3 Arrhenius Behavior of Carbon in H_2

In addition to the laboratory efforts, analysis of the erosion phenomena was pursued by Hercules. Dr. T. Wallace of LANL, under contract to Hercules, developed a recession rate model for graphite. Model predictions in the range of 2200 to 3000 K are compared to the BNL data in Figure 4.9-3. Correlation is seen to be quite good. Extension of the model to carbon-carbon and the coating systems was underway at program's end.

Near the end of the program it became clear that the former Soviet Union (FSU) had made significant advances in materials research. One of these, development of metal carbides, had great potential for the SNTP engine. With this material, coatings for the hot frit and nozzle could be minimized and/or eliminated and system reliability greatly increased. Grumman and NPO Lutch of the FSU negotiated a contract which was approved by the Russian government to supply zirconium carbide and niobium carbide samples for testing by the Program. However, the SNTP Program was stopped prior to implementation of the contract.

4.9.3 Advanced Instrumentation

Demonstration and development of PBR technology required a series of tests for technology / component development and demonstration engine testing. Demonstration and development tests require measurement and data acquisition of a multitude of physical

parameters. Advanced Instrumentation focused on measurements whose requirements could not be met with off-the-shelf instrumentation or by straight forward extension of existing technologies. The primary goal of the Advanced Instrumentation technology effort was to provide advanced instrumentation for measurements required by the other SNTP program elements. Advanced Instrumentation requirements and solutions cut across many SNTP program WBS elements. SNTP program management established Advanced Instrumentation as a separate WBS element in order to improve management visibility, accelerate key developments, avoid duplication, focus the efforts, better coordinate the activities and manage the down selection process. The key tasks involved in this effort were:

- Lead in identification of needs/requirements for advanced instrumentation.
- Identify, evaluate and recommend feasibility of advanced instrumentation methods/ techniques for measurement requirements.
- Evaluate, develop and demonstrate feasibility of advanced instrumentation and develop conceptual designs to an extent sufficient for the user WBS element to take over implementation of the instrument in their test apparatus.
- Transfer technology/data to engineering/test teams.
- Implement advanced instrumentation in the test apparatus in cooperation with the design/test apparatus team.
- Ensure that requirements for advanced instrumentation are included in apparatus and test facility designs.
- Initiate and make down select recommendations between alternative technologies.

The advanced instrumentation effort focused on several areas, including:

- High Temperature Instrumentation (main area of emphasis)
  - High Temperature Thermocouple Probes
  - Imaging Pyrometer (Non-invasive, Non-contact, Remote, Detailed Surface Temperature Distribution Measurement)
  - Capillary Probe
  - Direct Gas Temperature Measurement Via Raman Spectroscopy
- Exit Gas Species Measurement (Incipient Failure Detection)
- PIPET/DE Advanced Instrumentation
- Instrumentation Screening/Testing
- Optical Hetrodyne Hot Chamber Density Measurement
- ES&H Advanced Instrumentation
- Data Acquisition Coordination

Advanced instrumentation accomplishments included generation of a detailed Development Plan that included technical goals, risk assessment, critical issues identification/ resolution for efforts surrounding each of the instruments and areas of focus identified. Task

schedules, test plans and down select evaluation points are included in this Development Plan. Initial technical assessment activities for High Temperature Instrumentation, Exit Gas Species Measurement Via Raman Spectroscopy, and Optical Hetrodyne Hot Chamber Density Measurement were started and reported at the program meetings. Each of these measurement techniques was aimed at meeting a specific measurement need identified for application in various tests. The level of technical readiness for the instrument areas varied from proof of principle to top level conceptual design for implementation. Some bench scale instrument design and performance analyses were completed.

Program priorities in 1992 were focused on design and development of the fuel element and the upcoming NET experiments. Consequently, funding was not available to pursue long lead endeavors, such as Advanced Instrumentation. The Program had identified optical thermal imaging of the hot frit as highly desirable for future NET, PIPET and Demonstration Engine testing. Consequently , Grumman, with internal funding, demonstrated the experimental feasibility of the optical imaging pyrometer. Using a bench-scale system, researchers obtained an optical image of the temperature distribution inside a hot tube (~1500 K) that compared well with a temperature profile generated by thermocouples. This test series validated the feasibility of performing such measurements, and identified issues for extension of the measurement technique to actual test geometries, environment and temperatures (up to 3500 K).

4.9.4 Modeling and Analysis

The modeling and analysis activities associated with the successful development of a space nuclear system span almost all of the different program WBS elements. There is considerable overlap among many of the overall SNTP activities such as conceptual design, detail design, pretest predictions, test data analysis, and safety assessment. In many cases, the analyses within different program elements utilize common models and codes to investigate similar phenomena and coordination of the activities is desirable for efficient use of overall program resources. The goals of the modeling and analysis effort were to develop, verify, and validate the generic mathematical models required by the SNTP program. This specifically involved ensuring model commonality across the different organizations and efforts of the program, and that a common database of modeling parameters and material properties was used. Coordination to ensure that the different analytical techniques were validated and give the correct results in areas where they overlap (such as design and safety) was a primary goal. Model development and validation fell under this area of effort, with subsequent execution delegated back to the areas of effort most directly associated with the models. The modeling and analysis effort was subdivided into three areas:

- Thermal Hydraulics
- Reactor Physics
- Fuel Performance
- Materials Data Base

Thermal-hydraulic models were considered essential to the entire SNTP design effort, from conceptual design of the early test systems through safety assessments and full-scale testing. Substantial development efforts resulted in several useful codes that were applied to

fuel element analysis. Plans for these codes included full documentation and verification via experiments. All system components were to be modeled during the course of the program, and was to be integrated into an overall SNTP system thermal-hydraulic model. The thermal-hydraulic modeling effort proceeded along several parallel paths:

- Basic research into understanding flow through a heated particle bed.
- Development of computer codes to analyze fuel element performance.
- Code and analytical tool validation via actual test data.
- Use of modeling codes for fuel element and reactor design.
- Development of codes for safety analysis.

Reactor physics models were also considered essential to the entire SNTP design effort, from conceptual design of the early test systems through safety assessments and full-scale testing. Work to date utilized enhanced versions of industry-standard computer codes. Key issues include the generation of additional scattering kernels, evaluating and upgrading decay heat models, modifying the MCNP code to calculate neutron generation time, evaluating the need for space-time kinetics, and developing a gamma source model for common use in the program.

The materials data base effort was centered around the creation and maintenance of a properties data base for common use throughout the SNTP program. This data base included mechanical, thermal, and nuclear properties for all of the materials used in the SNTP program. This compilation would significantly reduce the duplication of work done by each of the different team members, as well as minimizing confusion and differences in analyses caused by using different properties.

The effort devoted to SNTP modeling and analysis was substantial, and the accomplishments significant. Numerous industry-standard modeling codes were implemented, both in "stock" and modified form, in generating models, and many new codes with unique capabilities were created. Virtually all the SNTP test articles and system configurations were modeled to some extent, and many components were modeled as well. The Modeling and Analysis WBS created three distinct areas of effort, although in reality much overlap exists between Thermal-Hydraulics, Reactor Physics, and Material Properties, especially at the systems level.

Thermal-Hydraulic Accomplishments

The SNTP thermal-hydraulic modeling work was done within the Fuel Element area of effort. Babcock & Wilcox upgraded the TEMPEST computer code by Battelle to enable it to be utilized on the NET, Fuel Element, Engine, and Nuclear Ground Test WBS Elements. TEMPEST was used to evaluate the thermal/hydraulic response of particle bed fuel elements and the feed and exhaust passages that duct coolant to and from them. In parallel, SNL developed the F2D computer code, and BNL developed the SIMBED set of computer codes. The F2D computer code is a general-purpose, two-dimensional, fully compressible thermal-fluids code that models most phenomena found in experimental environments with coupled fluid flow and heat transfer. The SIMBED computer codes include two- and three-dimensional, compressible flow thermal-fluids codes designed specifically for analyzing particle bed fuel elements. The SNTP system as a whole was also modeled with the SAFSIM general systems code, and several new system modeling codes were developed by the SNTP team.

The Flow Instability Test (FIT) series of experiments sought to benchmark the analytical codes used to quantify the temperature and flow-rate regimes in which potential flow instabilities could occur in a particle bed. Preliminary tests, conducted by BNL, successfully observed divergence in several areas of the simulated bed at certain temperature rise and flow rates. These results would be used to establish the engines operating boundaries Subsequent tests were in planning stages.

Reactor Physics Accomplishments

Substantial efforts were directed at modeling the Particle Bed Reactor and its components during the course of the SNTP program. The MCNP neutral particle transport code, an industry standard, was used to model the SNTP fuel elements and reactor in 1D, 2D, and 3D forms, and in various configurations. MCNP was also used to model the PIPET reactor, the CX reactor, and the NET apparatus. The CX campaign was used to benchmark the different modeling codes, including MCNP.

In addition to MCNP, ORIGEN2, another industry standard, was used to model reactor physics, notably decay heat and fission product inventory. Other codes used for this effort include CINDER and DKPOWER. Empirical models, such as the Way-Wigner formulation, were also used in this context.

Several enhancements to the industry standard codes were required to complete reactor designs and to perform safety assessments of those designs. These enhancements were made necessary by the unique requirements of the SNTP program, and address the key issues identified during the modeling and analysis effort. Some of these enhancements were accomplished, while others were identified as focal points for the modeling effort's future activities. The modified codes were made available for use by all of the different SNTP activities in a consistent manner.

Reactor dynamics and controls analysis was performed with the KINETIC code, developed by BNL during the course of the SNTP program. the need for spatial kinetics in analyzing a PBR-based compact flight engine was addressed and was found to be of secondary importance. However, there may be some operating conditions (such as startup) or reactor configurations (such as a driven PIPET core) which may require spatial kinetics. An evaluation was to be made of this need by examining the full range of SNTP engine and test facility operating conditions.

Fuel Performance Accomplishments

The HEISHI code was developed by SNL to aid in analysis, prediction, and optimization of fuel characteristics for use in SNTP. Calculational results include fission product release rate, fuel failure fraction, mode of fuel failure, stress-strain state, and fuel material morphology. HEISHI contains models for decay chain calculations of retained and released fission products, based on an input power history and release coefficients. HEISHI also contains models for stress-strain behavior of multilayered fuel particles with creep and differential thermal expansion effects, transient particle temperature profile, grain growth, and fuel particle failure fraction. The HEISHI code is intended for use in analysis of coated fuel

particles for use in particle bed reactors; however, much of the code is geometry-independent and applicable to fuel geometries other than spherical. The code was documented and released as SAND94-0169, August 1994.

Materials Database Accomplishments

A materials data base was compiled by assembling information gathered from the various areas of effort.

4.9.5 System Simulation

The System Simulation effort centered around developing, validating, and maintaining system level dynamic mathematical models of all SNTP systems. This effort was also meant to support the development of instrumentation and control systems. This includes real-time execution of math models, incorporation of actual hardware, and development and integration of control systems to enable real-time, hardware-in-the-loop simulation in support of all SNTP tests from NET to a flight engine. The System Simulation effort would also have supported test operator training, test plan development, and data acquisition systems development. The System Simulation team closely coordinated activity with members of the Analysis and Modeling team to assure the highest math model fidelity. This effort centered on three elements:

- Nuclear Element Test (NET) Simulation
- PIPET Simulation
- Demonstration Engine Simulation

NET simulation efforts coordinated closely with the Modeling and Analysis efforts involving NET, and with instrumentation and ICS efforts. The other simulation efforts were in initial stages at termination, building off the work accomplished for the NET simulation. Full simulations were required to support both PIPET and ground test simulations. Since flight-test was outside the scope of the SNTP program, efforts directed at the last of the above-listed elements centered on understanding the differences between a ground-test and a flight-test engine.

The chief accomplishments of the System Simulation area of effort centered around the NET series of experiments. NET simulation supported development of the NET flow control system. The simulation modeled the thermal and flow response of the NET experiment, and was interfaced in real-time with the Grumman Net Flow Controller (GNFC). The simulation was developed in parallel with other NET models, and was designed to incorporate experiment-derived updates. The simulation was developed from non-real-time codes developed under the Modeling and Analysis activities.

The GNFC was relatively simple as compared to what was necessary for the control of the subsequent planned tests and the demonstration engine. The control scheme selected for the more complex systems was developed by MIT and SNL. This was a time-optimal reactor control law which provided a method of closed-form control to adjust reactor power by many orders of magnitude in mimimum time and with minimum overshoot. It uses the rate of

change of reactivity as the control signal, and forms of this control law were sucessfully tested at the MIT Reactor (MITR) as well as the ACRR.

Plans for PIPET and Demonstration Engine (DE) simulation were tied to the development activities for those efforts, and were to increase in scope as the program focus shifted from NET to PIPET and then to the DE.

4.9.6 Integrated Control System

An intelligent, autonomous Integrated Control System (ICS) was required for the SNTP system. To this end, development of an ICS that provides autonomous engine control during all anticipated and unanticipated engine transients was initiated. The ICS is required to ensure the safe and reliable operation of the SNTP system during all modes of operation.

Planned development activities for the ICS centered on five areas of effort. These were:

- Conceptual Design
- Signal Processing Software
- Knowledge Processing Software
- Integration
- System Modeling

The first three areas constitute the research, development, and design necessary for a critical design review (CDR). The fourth area is the final design, procurement of hardware, and integration into a NTR engine. The fifth area supports testing and validation of the software.

A Development Plan was prepared for the ICS effort, and included identification of areas of risk and critical issues. Key experts outside the SNTP team were identified to provide input on ICS development should the combined expertise of the team prove insufficient. A top-level architecture was developed for the ICS. The ICS effort was closely tied to System Simulation activities, especially development of the Grumman NET Flow Controller.

4.10 SEI Engine Study

4.10.1 Overview

A six-month study effort was conducted in FY 93 to assess how SNTP engine technology would apply to NASA Space Exploration Initiative (SEI) mission requirements. The study, conducted under the technical direction of NASA Lewis Research Center (LeRC), evaluated various implementations of SNTP's PBR technology to a set of requirements geared towards piloted missions to Mars, and performed trades of various design options.

The study effort covered a range of topics related to nuclear thermal propulsion and its application to piloted Mars missions. SEI requirements were reviewed and codified, and three engine cycles were identified for study. The implications of these cycles on reactor and engine system design were assessed. Reactor decay heat, radiation shielding, safety, and reliability issues were also addressed.

The key difference between implementation of SNTP technology for missions discussed in Section 4.3 and for SEI missions is related to vehicle initial mass. The vehicles being considered for SEI missions to Mars are far more massive than those for other missions considered, and this has a dramatic impact on the trade between specific impulse and engine system mass. SEI missions benefit substantially more from increases in I_{sp} at the expense of engine mass, and the requirements provided by NASA LeRC call for engine thrust-to-weight ratios substantially lower than those targeted during the SNTP program. These facts lead to design solutions notably different than the baseline SNTP system's.

This section summarizes the findings of the SEI study. More detailed information can be found in SNTP-R-GRU-93-008, "SEI Engine Study Mid-Term Review." For brevity, discussions of the neutronics analyses and models, TPA trades and analyses, and other aspects of the study are omitted. Below are summaries of the cycles considered, a performance comparison of the different cycles, and a summary of vehicle integration issues.

4.10.2 System Cycle Concepts and Trades

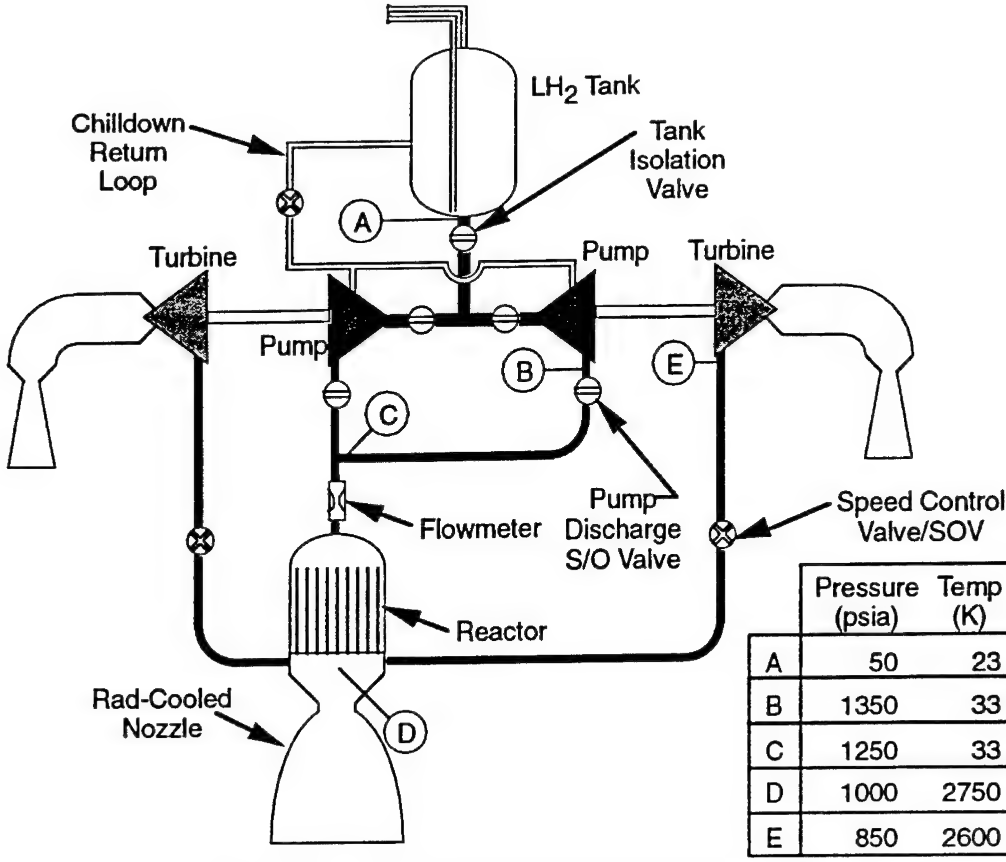
Three engine system cycles were analyzed during the course of the study. The first, a hot bleed cycle, most closely resembles the "baseline" SNTP system cycle. The other two are expander cycles, one full-flow drawing heat from the moderator, reflector, and a regen nozzle, and one partial flow drawing heat from dedicated fuel elements. These cycles are depicted in Figures 4.10-1, -2, and -3.

Expander cycles normally lead to heavier systems, adversely impacting thrust-to-weight. However, the increased premium placed on Isp by the SEI missions makes expander cycles more attractive. Figure 4.10-4 illustrates the gains in specific impulse a typical expander cycle offers over a bleed cycle. To approach the expander cycle I_{sp}'s, a bleed cycle must incorporate a high-temperature turbine, requiring a substantial development effort.

Figure 4.10-5 depicts performance for the partial-flow expander cycle. This design option provides significantly greater performance than the full-flow expander cycle, which requires regenerative cooling of the nozzle and subsequent loss of I_{sp}.

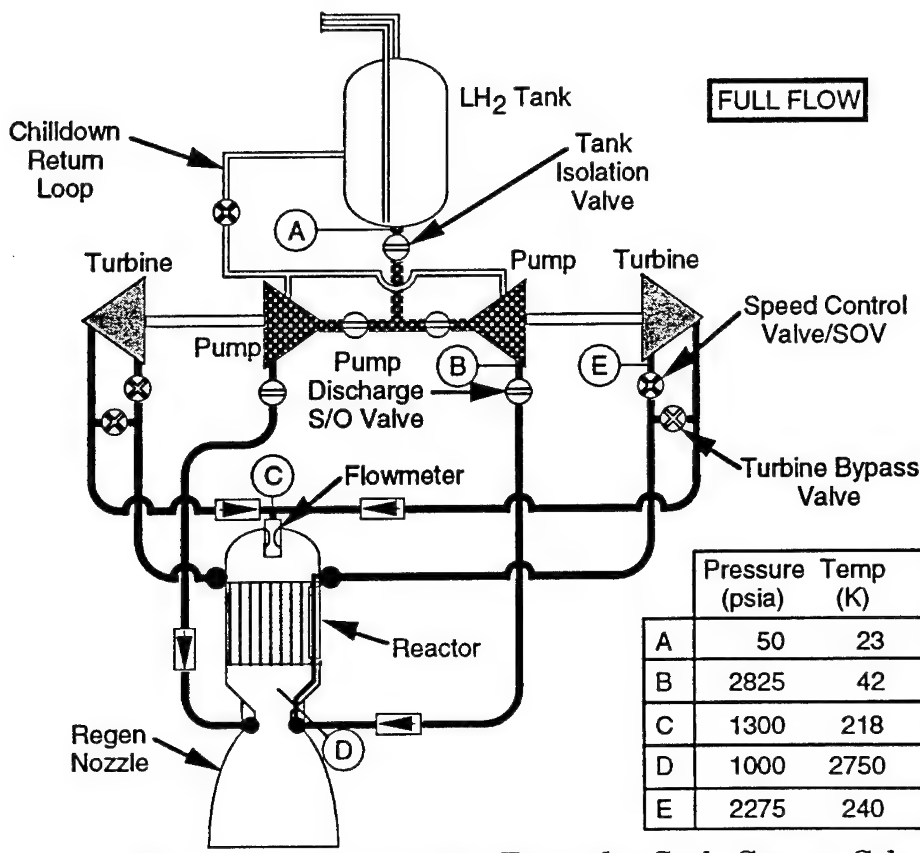
Figure 4.10-6 provides mass breakdowns and related data for the three cycles considered. As expected, the hot bleed cycle is the lightest. The partial flow expander cycle is only marginally heavier, however, while the full-flow expander cycle masses substantially more than the other two. The full-flow system's additional mass derives primarily from the metallic pressure vessel and nozzle that replace the carbon-carbon PV/nozzle used in the other two cycles. The carbon-carbon pressure vessel and nozzle is not readily integrated into the SNTP engine, since the heat deposited in these components must be removed and used to drive the turbine.

Based on performance, and the greater bias towards I_{sp} at the expense of engine mass, the partial-flow expander cycle is clearly the preferred approach for SEI missions, based on the groundrules and level of effort of this study. For approximately 300 lbs, or 10%, additional mass, the partial flow expander cycle provides 30 seconds more I_{sp} than the hot bleed cycle. It outperforms the full-flow expander by 20 seconds or more.



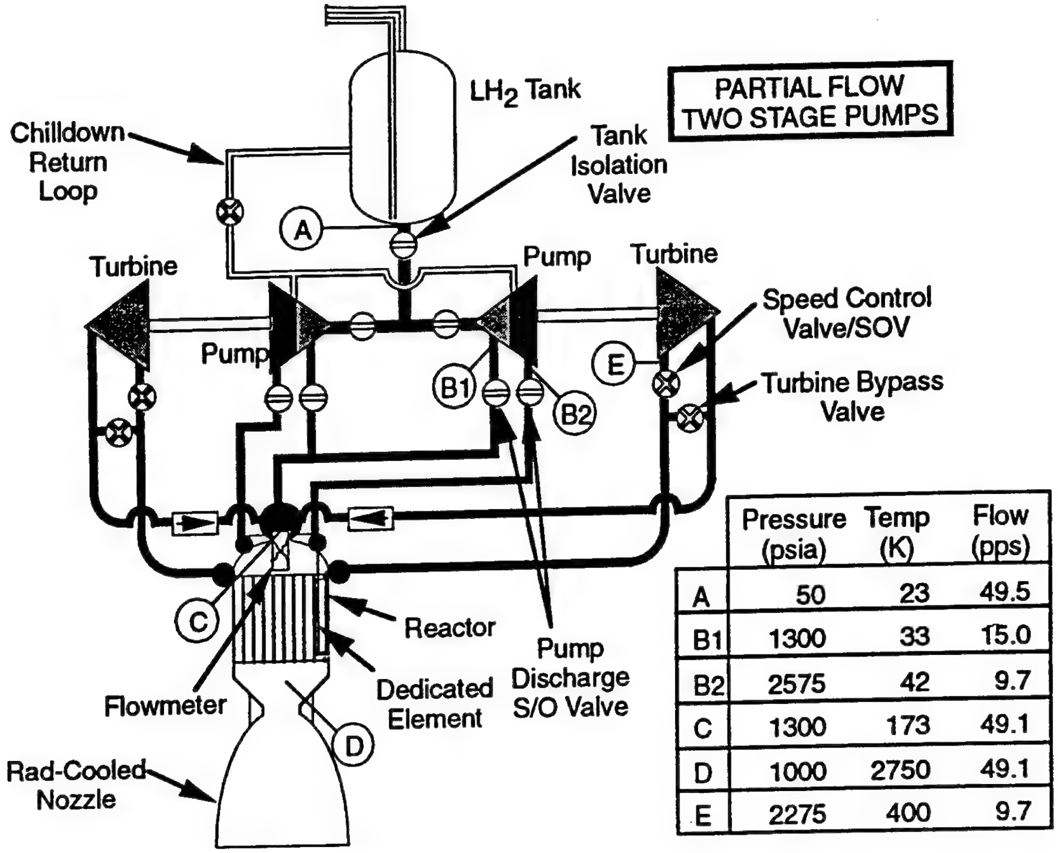
	Pressure (psia)	Temp (K)	Flow (pps)
A	50	23	49.5
B	1350	33	24.7
C	1250	33	24.5
D	1000	2750	49.1
E	850	2600	0.75

Figure 4.10-1 Hot Bleed Cycle System Schematic



	Pressure (psia)	Temp (K)	Flow (pps)
A	50	23	49.5
B	2825	42	24.7
C	1300	218	49.1
D	1000	2750	49.1
E	2275	240	24.7

Figure 4.10-2 Full-Flow Expander Cycle System Schematic



	Pressure (psia)	Temp (K)	Flow (pps)
A	50	23	49.5
B1	1300	33	15.0
B2	2575	42	9.7
C	1300	173	49.1
D	1000	2750	49.1
E	2275	400	9.7

Figure 4.10-3 Partial-Flow Expander Cycle System Schematic

4.10.3 Vehicle Integration Issues

In addition to decay heat removal and radiation shielding for propellant boiloff mitigation (issues associated with any use of nuclear thermal propulsion), the SEI mission requirements warrant consideration of additional vehicle integration issues. Notably, since the vehicle is piloted, radiation shielding must be sufficient to protect the crew. Additionally, the likely need for multiple engines requires consideration of interactions between the engine cores.

Decay Heat Management

The study assessed the requirements for decay heat removal after engine operation, and compared open-loop and closed-loop cooling schemes. It was concluded that, based on typical SEI mission profiles, there was no mass advantage to closed-loop cooling, and that open-loop cooling is preferred.

Radiation Shielding

Engine system mass estimates include an internal shield sized to preclude propellant boiloff due to neutron and gamma leakage from the reactor. This shield is inadequate to protect a crew, and additional external shielding is necessary to provide proper protection. Graphite is the preferred material for both the internal and external shields. Such a shield

was conceptually designed, and is estimated to mass approximately 6100 lbs. This mass is independent of chosen engine cycle, and is derived from NASA radiation specifications. Shield mass is closely coupled to vehicle configuration, and can be traded vs vehicle design options to minimize overall mass.

Engine Clustering

Assessments indicate that neutronic interactions between clustered engines are negligible at separation distances of 5 meters (pressure vessel to pressure vessel) and that minimal interaction exists at 3 meters. The likelihood that high expansion ratio nozzles will be used may be more of a driver on engine spacing than possible interactions. Interactions can also be effectively mitigated by side-wall shielding on the engines.

4.10.3 Conclusions

SNTP engine preliminary designs were developed that could meet the SEI requirements specified by NASA LeRC. Three engine cycles were studied: Hot Bleed (SNTP Baseline), Full-Flow Expander, and Partial-Flow Expander.

Of the three engine cycles considered, the partial-flow expander cycle clearly outperformed the other two. Although the resulting system massed marginally more than the bleed cycle, the tens of seconds of additional specific impulse more than offset the mass penalty for the SEI mission. The partial-flow system provided greater performance than the full-flow expander, while massing substantially less.

The partial-flow system did not require heat from the nozzle and pressure vessel and could therefore benefit from its use of a carbon-carbon radiatively-cooled nozzle. However, this component requires development, unlike the full-flow system's regeneratively cooled nozzle, which was based on proven technology.

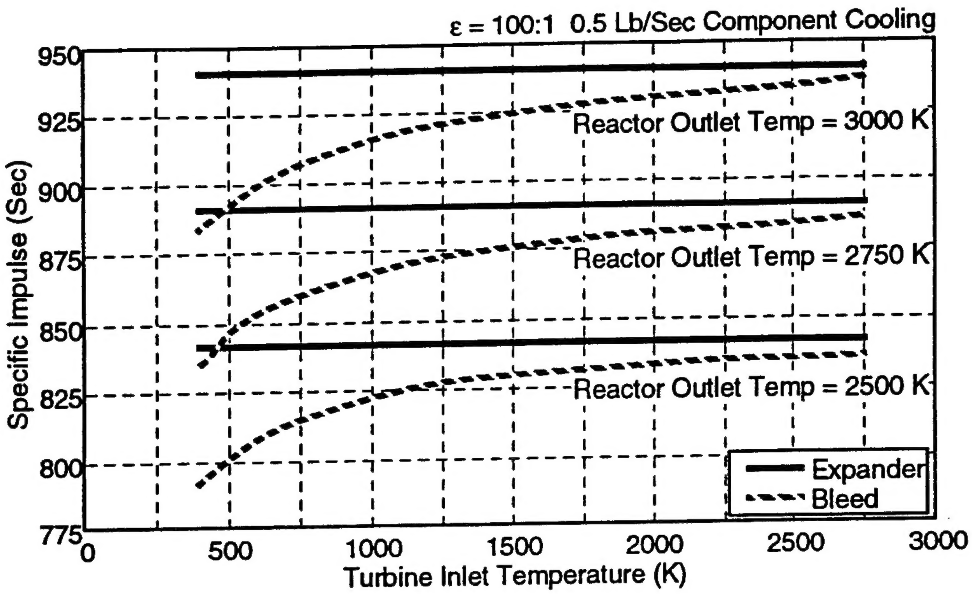


Figure 4.10-4 Engine System Performance - Bleed and Full-Flow Expander Cycles

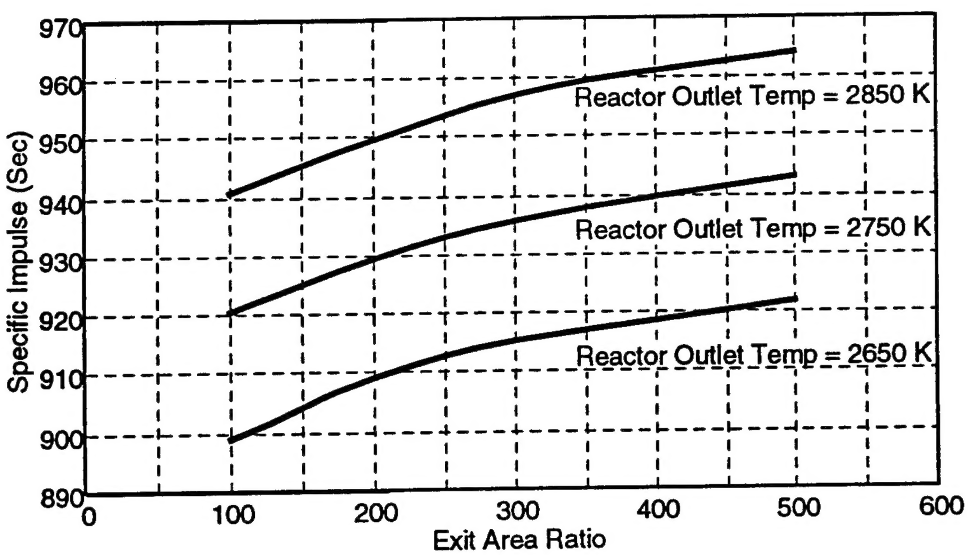


Figure 4.10-5 Engine System Performance - Partial-Flow Expander Cycle

Component (Masses in Lbs)	Hot Bleed	Partial Flow Expander	Full-Flow Expander
Pressure Vessel	158	158	666
Nozzle Assembly	388	397	770
Upper Dome	79	79	233
Control System	130	130	130
TPA System	282	359	271
Prop Mgmt System	278	486	416
Instrumentation	65	65	65
Thrust Vector Control	78	78	78
Total (Unshielded)	2505	2800	3677
Internal Shield	508	508	508
Total Engine System Mass	3013	3308	4185
Thrust (Lbf)	45520	45702	44970
Thrust/Wt (Unshielded)	18.2	16.3	12.2
Thrust/Wt (Shielded)	15.1	13.8	10.8

Figure 4.10-6 Engine System Mass Data

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